School of Engineering and Sustainable Development

One Utility for Sustainable Communities Modelling and Optimisation of Utility–Service Provision

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Abstract

Utility–service provision is a process in which products such as water, electricity, food, gas are transformed by appropriate devices into services satisfying human needs such as nutrition, thermal comfort, and wants such as e.g. entertainment. Utility products required for these processes are usually delivered to households via separate infrastructures, i.e. real-world networks such as electricity grids, water distribution systems or gas distribution networks. Additionally, they can be supplemented sourced locally from natural resources, e.g. electricity can be obtained from sun or wind. The main objectives of the research are to numerically evaluate feasibility of alternative approaches to utility–service provision problems and automatically generate suggestions of such alternative approaches, using knowledge base of present and future technologies and devices. These objectives are achieved via a simulation system implemented in C# and .NET 4.0 that is composed of the following blocks: an interface to define the utility–service provision problem (problem formulation), an interface to define candidate solutions (transformation graphs), a computational engine to analyse the feasibility of transformation graphs, a heuristic search algorithm to generate transformation graphs and a XML database.

The core of the proposed approach is a simulation system that carries out a feasibility study of transformation graphs. A transformation graph describes direct and indirect transformations of products into defined services or other products using various devices. The transformation graphs are represented in a form of standard directed graph where devices, product storages and services are nodes and edges represent product and service carriers. In the adapted approach each product has associated storage. The information about products, services and devices is used to create a visual representation of the content of the database - a Mastergraph. It is a directed hypergraph where services and product storages are nodes, while devices are edges spanning between. Since devices usually connect more than two nodes, a standard graph would not suffice to describe utility–service provision problem and therefore a hypergraph was chosen as a more appropriate representation of the system.

Two methods for defining transformation graphs are proposed. In the first one the candidate solutions are constructed manually. Additionally, an interface to calculate shortest paths between two products or a product and a service in Mastergraph was developed to simplify the manual process. In the second method, the transformation graphs are automatically generated using heuristic search approach developed for this model.

The functionalities of the proposed approach are presented through case studies. A benchmark case study based on the literature is analysed and compared with automatically generated solutions that vary in terms of energy and water delivered by the infrastructure as well as the total cost of supplying and removing products. These case studies showcase how the use of natural resources, recycling of some of the products that would normally be disposed, or simply the use of alternative devices have impact on the total cost and the amount of water and energy delivered by the infrastructure.

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Glossary of key terms and definitions

Basic definitions used in this thesis are introduced in this section. At the same time these concepts form elements of the proposed approach to model utility–service provision that are explained in more details in Chapter 3.

Community is a group of people living in the same locality and under the same government. It can be also perceived as a settlement that shares common values [1].

Device is an appliance that uses technologies to transform one or many products into other products (e.g. a three-blade wind turbine transforms wind energy into electrical power, or a diesel generator transforms diesel fuel to electrical energy) and/or into services (e.g. electric space heater transforms the utility product *electricity* into a service *thermal comfort - heating*). The transformation must specify the products/service, their quantity used by the device, and the *maximum throughput*, i.e. how many times device can operate according to the transformation during one time step. More detail about devices can be found in Section 3.3.1.

Fundamental need is an essential need for an individual to survive. Fundamental needs must be distinguished from wants. According to Dean [2], everybody can recognise that there are things in life that they might want that they do not need and things that they might need that they do not want. It is sometimes suggested that needs are absolute, while wants are relative. Fundamental needs remain the same at all times and are uninfluenced by cultural changes [3]. What is changing is the way in which these needs are satisfied. Needs considered in this research are discussed in Section 3.3.3.

Household is defined by the Department for Communities and Local Governments as "one person living alone or a group of people (not necessarily related) living at the same address who share cooking facilities and share a living room or sitting room or dining area" [4, p. 2].

Mastergraph is a representation of the entire content of the XML database in the form of a directed hypergraph. The rationale behind using hypergraphs is that standard graphs provide only one to one mapping between nodes and edges while in utility–service provision device usually uses more than one product (represented as a node) which can be transformed via a device (represented with an edge) into another product or service (also represented as a node). Mastergraph is explained in detail in Sections 3.3 and 4.3.3.

Problem formulation consists of a set of requirements and constraints. In this thesis it is a detailed specification of the utility–service provision problem that will be solved. Further information is detailed in Section 3.4.

In this research different types of **products** are distinguished. The term **utility products** is reserved for products that are provided by utilities, such as electricity, water, gas, etc. **By-products** are products obtained via transformation that will be further used, e.g. clean water from recycling, solid waste than can be processed (e.g. in solid waste burners), greywater collected from showers or washing machines, etc. **Products from nature** include products harvested locally from natural resources, e.g. solar irradiation, wind, rain etc. **Waste products** are products that cannot be processed and need to be removed from the system. Products are necessary to deliver certain services and therefore satisfy human needs. Some of them can be used to replace the others (e.g. drinking water can be harvested from rain and recycling and thus reducing the necessity to deliver it via utility). Information about products is detailed in Section 3.3.2.

Secondary need is derived from fundamental need (e.g. adequate nutritional food can be split into two secondary needs: *hot food* and *cold food*). In contrast to fundamental needs, they may change in time or vary for different cultures [3]. However, not all fundamental needs can be split into secondary needs. In the context of this research, utility services and products provided by one or several utilities satisfy directly some but not necessarily all secondary needs. The fundamental needs are then satisfied by the provision of utility products and services indirectly.

Service is a process of satisfying a **secondary need**, e.g. supply of drinking water, nutrition, partial body cleaning, etc. Services contribute to satisfying fundamental human needs indirectly. Each fundamental need can be satisfied by delivering different services, e.g. the fundamental need for clean environment is divided into several secondary needs, i.e. clean interiors, clean clothes, washing dishes. Each of the secondary needs can be further divided into services. However, to satisfy the need not all services must be delivered at once, e.g. dishes can be washed at lunchtime, whilst clothes washed later in the day. Services considered in this research are discussed in Section 3.3.3.

Technologies are required by devices to transform one or more products into another product(s), for example, the device *shower with electric water heater* uses technologies: water pump and power generation. Further information is detailed in Section 3.3.4.

Transformation graph is a candidate solution to a specific utility–service provision problem at a household or a community level, using the information about devices stored in the XML database. It is a standard directed graph where each node is a device, a storage or a service and each edge is a product or service carrier. The structure of transformation graphs is described in Section 3.5.

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Chapter 1

Introduction

This thesis introduces a new approach to support decision-making processes while considering more sustainable solutions for resource management in households or communities. This research was carried out as a part of the "All in One" EPSRC project under the reference number EP/J005592/1. In this project future utility–service provision possibilities were investigated, with the idea of replacing all utilities with just one to create sustainable and resilient communities.

This chapter introduces the term utility–service provision and the modelling approach in Section 1.1. The aims and objectives are listed in Section 1.2 while the contributions to science are summarized in Section 1.3. Section 1.4 lists the publications and presentations associated with the work presented in this thesis. The outline of the thesis and a short summary of each chapter is presented in Section 1.5. Section 1.6 describes research projects in which the developed approach was utilised in.

1.1 General introduction

Sustainability no longer has a single or agreed meaning. The concept of sustainability and sustainable development has been associated with a great variety of human activities. They are related to the efficient use of naturally available resources, non-renewable mineral and energy resources. According to Hasna, sustainability refers to a development of all aspects of human life affecting sustenance [5]. On the other hand, Allen claims that it is "the development that is likely to achieve lasting satisfaction of human needs and improvement of the quality of life under conditions that ecosystem and/or species are utilized at levels and in ways that allow them to keep renewing themselves" [6, p.23]. The most widely known definition is the one introduced in 1987 by the World Commission on Environment and Development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [7]. It is widely agreed that sustainability should help to reduce carbon emissions, mitigate and adapt to climate change, improve quality of life and human health. It can be also considered on different levels, starting globally, or nationally, in cities or communities, and finally by focusing on households and citizens.

According to the World Bank fossil fuel sources such as coal, oil, petroleum and natural gas accounted for 81% of the global energy consumption in 2014 [8]. The fossil fuels sources are predicted to be completely exhausted in the next 75 years at the current rate of their consumption [9]. On the other hand, there are 1.4 billion people lacking access to electricity, and without dedicated policies, the number will drop only to 1.2 billion by 2030 [10]. There is a need for rationalisation of demand, utilisation of local resources or creation of local grids or networks to improve the quality of life of inhabitants without social, environmental or economic degeneration [11, 12].

At the same time, avoiding carbon emissions is of paramount importance in the context of global concern for climate change effects, which might not only influence the availability of energy but increase its demand, especially in the residential built stock. These problems were addressed at the Paris conference in 2015. An agreement was proposed to limit the rise in temperature to 1.5 °C mainly to protect island states. These states are the most endangered by the sea level rise. By the end of the conference 195 countries published their action plans to reduce their greenhouse gas emissions. Industrialised countries are obliged to fund climate finance for poor countries, while developing countries can contribute on a voluntary basis [13]. However, according to the latest findings only three European countries (Sweden, Germany and France) are able to fulfil the promises they made by signing the agreement [14].

There are many ways that countries can become more sustainable. For instance, they can reduce the use of fossil fuels by replacing them with renewable energy, or introduce stringent regulation to force industries to reduce their emissions. In 2015 a set of 17 Sustainable Development Goals (SDGs) was introduced as a part of the 2030 Agenda for Sustainable Development [15]. The main goal of the Agenda is to create a sustainable future for the people, planet, prosperity, peace and partnership [15]. Each of the SDGs has associated set of indicators that will provide metrics to ensure progress towards a sustainable planet. Additionally, governments develop policies and technical standards for developers that define actions to protect the environment and reduce environmental impact of new-build and existing dwellings [16, 17]. Unfortunately, as governments change, the policies also change. Despite that, citizens can still make sustainable choices in their homes or neighbourhoods. It can be as simple as introducing recycling, or minimising the amount of waste produced, or reducing household consumption, or more complex, such as modifying homes to be near zero carbon. In order to do so, a more in-depth analysis of the processes that occur within a household and how utility products are delivered is required. Additionally, not all municipal governments must follow the footsteps of parties in charge. A very good example is provided by fifteen states that created U.S. Climate Alliance and vowed to uphold the Paris Accord, despite their country's assertion to leave it [18].

The research proposed in this thesis analyses how products are delivered (either supplied directly from infrastructure or by subsidising from other sources) to households and used within them. It also enables investigation of alternative approaches to the current utility–service provision solutions. The utility–service provision can be concisely explained as follows. Utility products are usually delivered to households via separate infrastructures, i.e. real-world networks such as electricity grids, water distribution systems, gas distribution networks. Some of the products can be supplemented by natural resources, e.g. rainwater can be treated to drinking water quality, electricity can be generated from wind, water can be extracted from air or ground. However, provision of different utility products in appropriate quantities does not itself guarantee that the required services will be delivered as the utility–service provision problem requires not only products but also appropriate devices. The core of the proposed approach is a simulation system that enables carrying out the feasibility analysis of utility–service provision problems. The approach also considers automatic generation of potential alternative approaches, using a knowledge base of present and future technologies and devices. The simulation system is composed of the following modules: an interface to define the utility–service provision problem, an interface to define candidate solutions (transformation graphs), a computational engine to analyse the feasibility of solutions and an XML database. Both interfaces and the computational engine are developed in C# and .NET 4.0, while the XML database is implemented using eXist-db, an open source native XML database system. The purpose of the XML database is to store information about products, devices, technologies and services, which can be used to define utility–service provision problems and candidate solutions using corresponding interfaces. Utility–service provision problems and candidate solutions are defined using XML format. The proposed approach can be applied both to households and communities. In this thesis the emphasis is on the households. However, the developed simulation system enables analysis of communities as well. Therefore, some of the devices stored in the database are only applicable for community scale solutions, while others are suitable only for households. Additionally, utility–service provision allows to test scenarios at different points in time by tagging technologies with the year of first availability. This was particularly useful in the “All in One” project, where futuristic scenarios were evaluated.

1.2 Aim and Objectives

The main aim of this research is to investigate the feasibility and sustainability of alternative approaches to current utility–service provision approaches. These approaches include substituting some of required products that are delivered by utilities by naturally available resources, introducing recycling within a household, reducing the amount of utility products delivered to a household. Objectives for this research are as follows:

- To conduct a requirement analysis to identify fundamental human needs that can be satisfied by the provision of products. It includes investigation of water and energy consumption patterns as well as household waste and recycling rates in the past and present based on a statistical data. The main sources of information have been: (i) journal and conference papers, (ii) reports from government departments (e.g. DEFRA, U.S. Environmental Protection Agency), (iii) reports from consultancies and research institutions (e.g. European Competition Network's reports, U.S. Sandia Laboratory); (iv) technical data of commercially available products; (v) academic databases (e.g. Civil Engineering Database, Directory of Open Access Journals, Information Bridge: Department of Energy Scientific and Technical Information). This objective is addressed in Chapter 2.
- To investigate a wide range of products and services as well as existing or not yet fully developed devices and technologies that satisfy basic human needs. The information about identified devices, technologies, products, services and needs is stored in an XML database. This objective is addressed in Chapter 3.
- To examine the feasibility of a proposed solution for a single household by the generation of all possible alternative solutions based on the investigated products, services, devices and technologies. The feasibility study is conducted using the developed simulation system that enables automatic generation of all possible alternative solutions based on the content of the XML database. This objective is addressed in Chapter 3 and Chapter 4.
- To analyse the structure and characteristics of utility–service provision network by using graph theory on a hypergraph that represent the entire content of the XML database (referred to as Mastergraph). The rationale

behind using hypergraphs is that standard graphs provide only one to one mapping between nodes and edges while in utility–service provision device usually uses more than one product (represented as a node) which can be transformed via a device (represented with an edge) into another product or service (also represented as a node). This objective is addressed in Chapter 4.

– To determine the optimal solution of automatically generated solutions that is balanced between the total cost of supplying products and removing waste products as well as the quantities of water and energy delivered from the infrastructure in the proposed solution based on heuristic approaches. The capital cost is not modelled in this approach. This objective is addressed in Chapter 4.
– To validate the developed methods through case studies for households. These case studies include work based on the projects "All in One" and "Consortium for Rapid Smart Grid Impact" and represent solutions to different utility–service provision problems.This objective is addressed in Chapter 5.

1.3 Contributions

The main contributions to knowledge are as follows:

1. A new conceptualisation of utility–service provision to households or communities using a detailed division to devices. In the developed approach a household or a community is considered as an input-output system. Various products are delivered to households/communities via infrastructures such as water distribution systems, electricity grid and gas distribution network. There are also naturally available products that can be used in household/-communities. All these products are transformed using various devices into other products or used to satisfy basic human needs. During these processes some waste products can be produced and they need to be removed from the system using wastewater infrastructure. This is further explained in Chapter 2.
2. An abstraction of household/communities to enable a quantitative analysis of solutions to utility–service provision problems. In the process the components and processes occurring within households/communities were analysed and decomposed, to understand what parameters and variables are influencing the system. Additionally, inputs and outputs were identified as various products, basic human needs were divided into services that

can be delivered by certain devices using the products. In the process of abstraction the devices were assumed to have a fixed ratio between inputs and outputs, i.e. no dynamics. This is further explained in Chapter 3.

3. A formalization of the executive model for simulation purposes. An XML database was developed to store information about devices, technologies, products, services and needs. The XML database provides a compendium of available and emerging devices that can be used in households to deliver services directly (so-called service devices), as well as convert some products into other products (so-called conversion devices). They can also be used by cities or communities to reduce environmental impacts, e.g. wind turbines can be used to support some of the electricity demand. The model has been divided into the following blocks: (i) a problem formulation, (ii) a candidate solutions (transformation graphs), (iii) a simulation system and (iv) the XML database. This is further explained in Chapter 3.
4. Development and implementation of the simulation system in C# and .NET 4.0. The developed simulation system is composed of the following blocks: an interface to define the utility–service provision problem (problem formulation), an interface to define candidate solutions (transformation graphs), a computational engine to analyse the feasibility of solutions and the XML database. The main functionality of this system is to assess whether a candidate solution (transformation graph) is feasible, i.e. meets all the requirements based on the constraints from the problem formulation. This is further explained in Chapter 3.
5. Quantitative analysis of households/communities product consumption. A simulation system utilises the database to analyse a proposed solution to a defined utility–service provision problem. The mass balances of all products used in the solution are calculated. Additionally, the overall cost of delivering and removing products from a household/community as well as quantities of products that must be supplied and removed by various infrastructures. This is further explained in Chapter 3.
6. Idea of representation of the candidate solutions in a form of directed graphs (transformation graph). The candidate solutions are visualised in a form of a directed graph, so-called transformation graphs, where each node is a device, storage or a service and each edge is a product or a service carrier. This representation enables a clear identification of the connections between each of the components This approach enables analysis of the resilience, vulnerability, robustness, and redundancy of candidate solutions. These topics are addressed in Section 3.5.
7. Idea of representation of the entire content of the XML database in a form of a directed hypergraph (Mastergraph) enables the use of graph meth-

ods to construct the candidate solutions for a defined utility–service provision problem. The properties of Mastergraph were analysed to determine the robustness, redundancy, vulnerability of utility–service provision network. This is further discussed in Section 4.2.

8. Developing and implementing heuristic search for feasible transformation graphs. Existing heuristic search approaches were analysed to establish whether one of them could be useful when automatically generating transformation graphs based on a problem formulation to a specific utility–service provision problem. However, none of the existing solutions were adoptable to the search of feasible transformation graphs. The algorithm is described in Section 4.2.2.
9. Validation of the developed approach on case studies. The model presented in Chapter 3 is used to simulate case studies presented in Chapter 5. The heuristic search approach presented in Chapter 4 is used to find alternative solutions that introduce recycling of some products and use of naturally available resources. These solutions are analysed based on the overall costs as well as drinking water and energy consumption. The case study presented in Section 5.3 is based on a real case study - a household located in Ilha Solteira in Brazil.

Research presented in this thesis is based on the model proposed by De Montfort University researchers in the “All in One” project. Therefore, the contributions 1 - 3 were developed jointly between the academics. The author of this thesis made significant input to contributions 4, 5 and 6. Finally, the remaining contributions were developed solely by the author of the thesis. The description of each partners’ input is specified in Section 3.7.

1.4 Publications and presentations

The work in this thesis was published in several journal and conference papers and presented at conferences and workshops.

1.4.1 List of publications:

A. Strzelecka, T. Janus, L. Ozawa-Meida, B. Ulanicki, and P. Skworcow *Modelling of utility-–service provision*, Proceedings of the Computer Systems Engineering Theory and Applications 15$^{\text{th}}$ Polish-British Workshop, 3$^{\text{rd}}$ International Student Workshop, Wroclaw, Poland, (2015).

A. Strzelecka, T. Janus, L. Ozawa-Meida, B. Ulanicki, and P. Skworcow *Utility–service provision as an example of a complex system*, Emergence: Complexity & Organization, 17(2):1-13, (2015). (Reference [19])

A. Strzelecka, P. Skworcow, and B. Ulanicki *Modelling, simulation and optimisation of utility-service provision for households: case studies*, Procedia Engineering, 70(0):1602-1609, ISSN 1877-7058, http://dx.doi.org/10.1016/j.proeng.2014.02.177 (2014). (Reference [20])

F. Karaca, P. Raven, J. Machell, L. Varga, F. Camci, R. Chitchyan, J. Boxall, B. Ulanicki, P. Skworcow, **A. Strzelecka**, L. Ozawa-Meida, and T. Janus *Single infrastructure utility provision to households: Technological feasibility study*, Futures, 49:35–48, (2013). (Reference [21])

A. Strzelecka, and P. Skworcow *Modelling and simulation of utility service provision for sustainable communities*, International Journal of Electronics and Telecommunications, 58(4):389–396, (2012). (Reference [22])

A. Strzelecka, P. Skworcow, and B. Ulanicki *Modelling of utility–service provision for sustainable communities*, Proceedings of the Computer Systems Engineering Theory and Applications 12^{th} Polish-British Workshop, Wroclaw, Poland, (2012).

A. Strzelecka, P. Skworcow, B. Ulanicki, and T. Janus *An approach to utility–service provision: modelling and optimisation*, Proceedings of the International Conference on Systems Engineering, Coventry, UK, (2012). (Reference [23])

B. Ulanicki, **A. Strzelecka**, P. Skworcow, and T. Janus *Developing scenarios for future utility provision*, Proceedings of the 14^{th} Water Distribution Systems Analysis, Adelaide, South Australia, (2012). (Reference [24])

1.4.2 List of presentations:

Participant in a round table at EuroScience Open Forum – Bringing nature back to cities – what's in it for business? 23 - 27 July 2016, Manchester, UK, *Sustainable waste management in cities, what are the issues?*

Invited Lecture at Wroclaw University of Science and Technology, Faculty of Electronics, 6 June 2016, Wroclaw, Poland *Selected aspects of computer simulations*

Presentation at a Student Seminar at Universidade Estadual Paulista UNESP, Electrical Engineering Department, 21 May 2015, Ilha Solteira campus - São Paulo, Brazil, *One Utility for Sustainable Communities: Modelling and Optimisation of Utility–Service Provision*

Presentation at the 14th Polish-British Workshop, 2nd International Student Workshop, 5 – 8 June 2014, Wroclaw, Poland, *An Approach to Optimize Utility–Service Provision for Sustainable Households*

Presentation at the 13th European Conference on Complex Systems, 16 - 20 September 2013, Barcelona, Spain, *Utility-Service Provision as an Example of a Complex System*

Presentation at the 12th International Conference CCWI 2013: Computing and Control for the Water Industry: "Informatics for Water Systems and Smart Cities", 2 - 4 September 2013, Perugia, Italy, *Modelling, simulation and optimisation of utility–service provision for households: case studies*

Presentation at the 13th Polish-British Workshop, 1st International Student Workshop, 6 – 9 June 2013, Wroclaw, Poland, *Towards Enhanced Sustainability of Households: Simulation of Utility–Service Provision*

Presentation at a Student Seminar at University of Palermo, Department of Architecture, 18 April 2013, Palermo, Italy, *One Utility for Sustainable Communities: Modelling and Optimisation of Utility–Service Provision*

Presentation at the International Conference on Systems Engineering, 11 - 13 September 2012, Coventry, UK, *An approach to utility–service provision: modelling and optimisation*

1.5 Outline of the thesis

The thesis is structured as follows, addressing the aims and objectives described in Section 1.2.

Chapter 2 presents the background and motivation for the research with the relevant literature review. Several fields were researched to develop the simulation system that will enable the feasibility analysis of a proposed solution (a transformation graph) or automatically generate a set of transformation graphs for a particular problem formulation. The chapter begins with the examination of literature devoted to human needs to identify the ones that can be satisfied by provision of products. It is followed by the analysis of national water and energy consumption patterns as well as household waste and recycling rates in the UK. In the next sections the concept of sustainability is reviewed together with the main approaches to assess the sustainability of cities, communities and households and approaches to solve utility–service provision problems. The chapter concludes with the summary of the projects in which the developed simulation system was used.

Chapter 3 describes the modelling approach to utility–service provision and explains each of the elements that form the simulation system: (i) the XML database that stores information about products, devices, technologies, services and needs; (ii) the problem formulation which consists of a set of requirements and constraints; (iii) the transformation graph - a candidate solution to a utility–service provision problem; (iv) a computational engine to analyse the feasibility of solutions.

Chapter 4 presents a heuristic search algorithm to optimise the automatic generation of transformation graphs. It also presents the approach to finding shortest hyperpaths in the hypergraph (Mastergraph) that represents the entire content of the XML database. The topology of Mastergraph is also analysed as it is required to find candidate solutions for utility–service provision problems.

Chapter 5 presents the use of the simulation system and the automatic generation in case studies. They include "All-in-one" solution for a household in a community in Scotland, and a real life household in Estrela da Ilha settlement in Ilha Solteira in Brazil investigated in the Global Innovation Initiative project called "Consortium for Rapid Smart Grid Impact".

Chapter 6 summarises the main conclusions and describes possibilities for further research.

Appendix A contains the manual for the graphical user interface (GUI) developed to manipulate data in the XML database as well as interfaces to define problem formulations and transformation graphs.

Appendix B contains basic concepts from set theory that are used throughout the thesis.

Appendix C (CD) contains the entire content of the XML database described in Chapter 3, the Mastergraph , the modified incidence matrix and matrices of inputs and outputs described in Chapter 4, the problem formulations for the case studies presented in Chapter 5. It also includes the source code for the XML Database Content Editor as well as the Simulation System developed in this thesis.

1.6 Projects

This research was a part of the EPSRC Sandpit project "All in One: Feasibility Analysis of Supplying All Services Through One Utility Product" under the reference number EP/J005592/1, [25]. The project started in October 2011 and ended in April 2013. There were four research partners involved: Cranfield

University, The University of Sheffield, De Montfort University and University of Leicester. The main question of the project: “Can a single utility product and/or infrastructure be sufficient to supply all household services and products that end users might want?” [26]. This question was focused on the future of utility–service provision in one hundred years’ time. The idea of supplying just one utility product, or supplying necessary products via one infrastructure is new and novel. Current state of utility–service provision is based mostly on water, gas, electricity, food and information that are delivered to household as well as waste that is removed, all via separate costly and resource intensive infrastructures. However, the All-in-One project gave an interesting perspective that all these utility products and the existing infrastructures that are required to provide them could be substituted by “the one”: either a product or an infrastructure. Moreover, this project could help to identify the existing challenges as well as gaps in science and technology that are preventing the vision of All-in-One to become a reality. Section 3.7 provides detail on the evolution of the All-in-One approach after the project ended as well as contributions of the researchers involved in the development of the modelling approach reported in this thesis.

The simulation system was used to assess the feasibility of satisfying all fundamental human needs by provision of one utility product. The case study investigated was a community in Scotland where “the one” is electricity. These case studies are described in detail in Chapter 5.

The second project that the simulation system was utilized for is the Global Innovation Initiative project called “Consortium for Rapid Smart Grid Impact” [27]. A single household from the Estrela da Ilha settlement in Ilha Solteira, located in the State of São Paulo (Brazil) was selected in order to investigate possibilities for improving electricity provision in the area, by substituting some of the demand from natural resources [28]. The case study contributed to one of the main focus studies in the project, i.e. investigation of all possible scenarios for rural communities to become energy independent [29]. This case study is described in Chapter 5.

Chapter 2

Background and motivation for research

2.1 Introduction

Utility–service provision takes into consideration processes that occur within households or communities. The main purpose of the processes is to satisfy human needs. Utility–service provision is focused on: (i) products that are delivered to a household/community; (ii) processes that occur within that household/community that aim to sustain their occupants; (iii) waste products that are generated and need to be utilized or removed. In the first instance human needs that can be satisfied by provision of products needed to be identified. They were later divided into secondary needs and services. The latter are considered for the purpose of the simulations and conceptualisation of a household/community. This analysis is summarized in Section 2.2. In the second instance a review of household consumption was conducted to identify the way people use products to satisfy their basic needs. Water and energy consumption was the main focus of this activity to help to identify devices used in households and how this has changed in recent years. Additionally, trends in waste production were analysed to identify possibilities to improve current situation (which translates to the content of the XML database), e.g. proposing solutions to generate energy from waste. These aspects are presented in Section 2.3. The development of the modelling approach is outlined in Chapter 3.

The remaining sections are focused on subjects relevant to establishing the context of this research. Section 2.4 focuses on reviewing literature on sustainability and sustainable development with the aim of specifying the approach adapted for this research. Subsequently, various sustainable communities are analysed in order to establish the most appropriate definition of the term. Section 2.5 reviews different approaches to assess sustainability of cities, communities and households. It is followed by summary of the “All in One” project in Section 2.6.

2.2 Human needs

There are many theories devoted to human needs. The first division that is often made is the distinction between human needs and wants. The former is considered as something we need to survive, that we might not necessarily want, whereas the latter is related to something we do not need to survive [2]. Another distinction is between instrumental (derivative needs) and non-instrumental (basic needs) [30]. In this approach the instrumental needs relate to what is needed to satisfy some needs (such as clothing or food) whereas the non-instrumental ones relate to needs that are fundamentally necessary for survival. The most well known was proposed by psychologist Abraham Maslow [31]. Initially, he divided human needs into five categories. His work is often represented in a form of a pyramid (Figure 2.1), where the most basic - physiological needs (for oxygen, water, nutrients, homeostasis, excretion, sleep, etc.) are at the bottom and the needs for self-actualisation (self-fulfilment through achievement) are at the top. The second category of needs are related to safety: physical security, security of resources, livelihood, family and possessions. The next ones are love and belonging (relationships, family, friendship and sexual intimacy) and self-esteem (self-identity and respect, confidence and respect from others). Later, Maslow expanded the original model to include three more needs: cognitive (the need to acquire knowledge and understanding), aesthetic (the need for creativity and the appreciation of beauty and structure) and transcendence needs (the need to help others achieving self-actualisation) [32].

Utility–service provision is focused on satisfying physiological needs as well as wants by delivering and disposing products from households/communities.

Basic human needs are the components required for survival as well as for physical and mental health. Those components include water, food, shelter, etc.

In this research only the basic fundamental needs are taken into consideration because they can be satisfied by provision of utility products. Thus the following needs are investigated: access to transportation, adequate level of personal hygiene, adequate quantity and quality of drinking water, clean and safe environment, clothes, economic security, entertainment/leisure, adequate level of comfort, adequate nutritional food, mental and physical health, physical activity, physical security, provision of adequate sanitation, [22]. It is worth mentioning

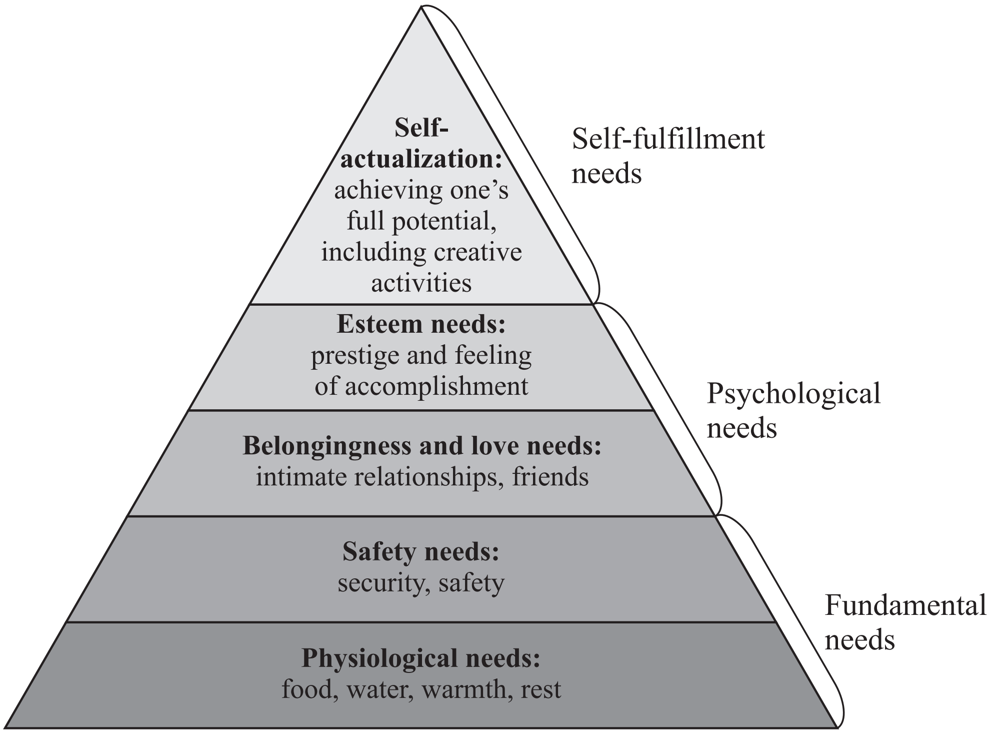


Figure 2.1: Maslow's hierarchy pyramid [33]

that the access to transportation need reflects the capability of a household/community to satisfy this need. Therefore, the main focus in the research presented in this thesis is on charging electric vehicles. Transport takes place outside of a household, which is not in the scope of this research. Therefore, this need is analysed in a limited matter. A secondary need is derived from fundamental need. In contrast to fundamental needs, secondary needs may change in time or vary for different cultures [3]. However, not all fundamental needs can be split into secondary needs. In the context of this research, utility services and products provided by one or several utilities satisfy directly some but not necessarily all secondary needs. Therefore, the fundamental needs are satisfied by the provision of utility products and utility services indirectly [23]. First services are delivered to satisfy secondary needs, which in turn, satisfy the fundamental ones. The complete list of needs that are considered in this research is presented in Section 3.3.

2.3 Utility products consumption statistics

An analysis of the utilities consumption was conducted in order to identify which needs can be indirectly satisfied by provision of products. Understanding of these trends is relevant from the perspective of future utility–service provision. Figure 2.2 shows how Britain's population as well as number of households have changed since 1970. In contrary to the accelerated growth of households, population rose very slowly between 1970 and 2016 [4, 34]. The rapid growth in the number of households reflects a trend for smaller households. The number of people living alone or in small families was increasing, but over the last 10 years the average number of people per household remained at 2.4 [35]. Figure 2.3 illustrates household occupancy in 2016. It is estimated that single person households accounted for 28% of all households in the UK [4]. This has implications both on the provision of appropriate housing as well as on energy and water use in homes. Energy and water consumption per person tends to be increasing when the number of occupants is decreasing, further discussed in Section 2.3.2 and Section 2.3.1 respectively.

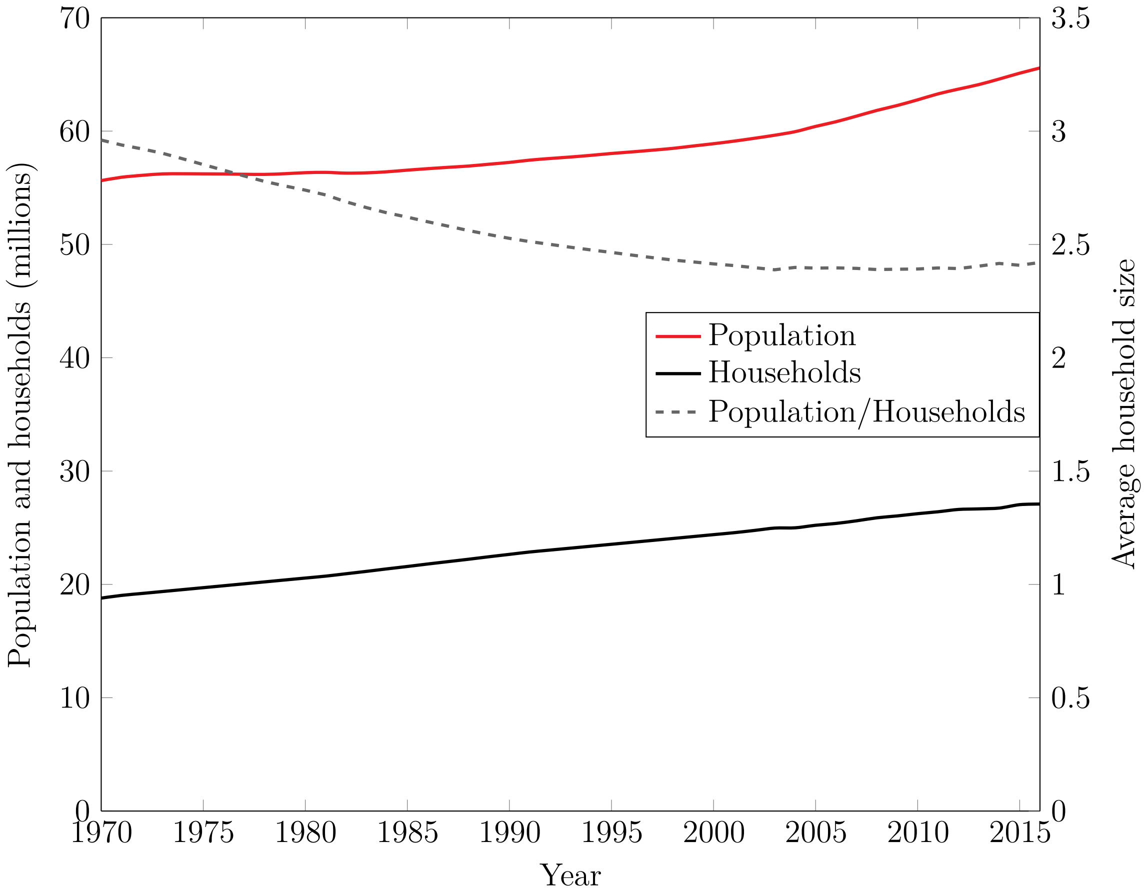


Figure 2.2: Population and households [4, 34].

A general review of water and energy consumption patterns in households in the UK over the last 40 years was conducted. The primary objective of this research was to identify which needs can be satisfied by provision of products. This information can be helpful when predicting future demands as well as determining necessary factors to satisfy human needs in general. The former is

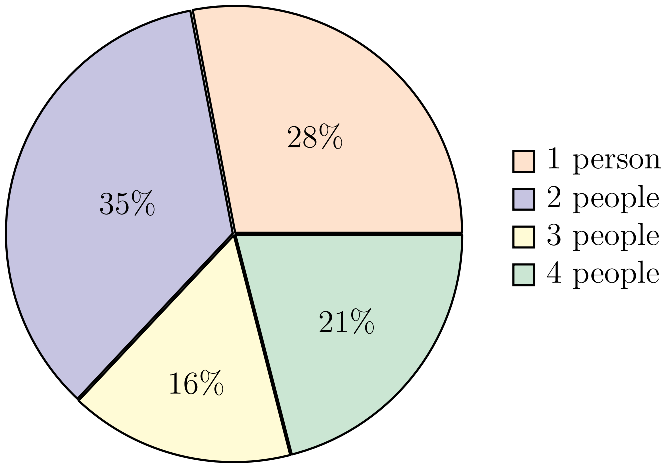


Figure 2.3: Household occupancy in 2016 [4].

directly connected to the "All in One" project, where the research was focused on investigating utility–service provision in 100 years time [26]. Predicting the future with a high level of certainty is inherently difficult. However, this uncertainty has not stopped scientists from trying. Friedman in his book "The next 100 years: a forecast for the 21st century" attempted to forecast the changes that can be expected around the world from the political and economic perspective [36]. Barnatt investigated 25 aspects that will shape the next few decades [37]. He also discussed how technologies and future challenges interrelate, for example nuclear fusion and future transport, or climate change and vertical gardening. Kaku interviewed over 300 scientists around the world in the attempt to find out what will happen in science and technology in the next century. He concludes the book with a description of a day in life in 2100, where people will rely heavily on artificial intelligence and computers [38]. This confirms the approach of many scholars that the dependency of people on technology and software is increasing [39].

The analysis of consumption patterns was conducted in order to understand how people's usage of products in households changed in the last 40 years. This information was necessary when populating the XML database. The purpose of the database is described in Section 3.3 and the content is listed in Appendix C. In Section 2.3.1 energy consumption within households over the last 40 years is discussed. The trends presented show the change that occurred and give possibility to predict future consumption. It also gives an insight in the type of devices that became obsolete as well as the ones that are becoming a necessity. Additionally in Section 2.3.2 water consumption in household is discussed. Section 2.3.3 discusses trends in waste produced in households in the UK.

2.3.1 Household energy consumption in the UK

In 2015 household consumption accounted for 29% of total UK final consumption of energy products [40]. The average household energy consumption in the UK is presented in Table 2.1. Energy consumption in households depends on several factors identified in the literature [41]:

- type of dwelling and its level of insulation [42, 43];
- external temperatures - it especially influences the amount of energy used for space heating [35, 44];
- technical factors such as the efficiency of the appliances used within a household, e.g. washing machines, dishwashers [45];
- lifestyle choices such as the number of times clothes are worn before being washed [46];
- number of people living in the household [47];
- age of the occupants [48, 49];
- time spent in the household [48].

Table 2.1: Average annual and daily energy consumption in households [50]

Fuel	Consumption (MWh/year)			Consumption (kWh/day)		
	Low	Average	High	Low	Average	High
Gas	8	12.5	18	21.9	34.5	49.3
Electricity	2	3.1	4.6	5.5	8.5	12.6

Figure 2.4 illustrates how the energy mix in the residential sector has changed since 1970. At the time almost 50% of energy consumed by households came from coal, coke and other solid fuels. This proportion dropped dramatically by 2005. The main reason for this change was the fact that environmental issues began to be recognised in energy policies and North Sea gas came on line [40]. Furthermore, government in the UK set out targets in 2002 of a 80% reduction of greenhouse gas emissions by 2050 [51]. Figure 2.5 illustrates how the household energy consumption increased in the past 45 years in absolute values. Gas consumption almost tripled in that time period while solid fuel consumption (which include: coal, coke and breeze, and other solid fuels) has dropped by 97% [40]. Nowadays, the primary sources of energy are gas and electricity. This energy is used for space and water heating, cooking, lighting and electrical appliances (Figure 2.6).

The major proportion of energy used within households is for space heating. It is estimated that it accounted for approximately 62% energy used in 2012 (Figure 2.6). Second major contributor is energy used for lighting and appliances,

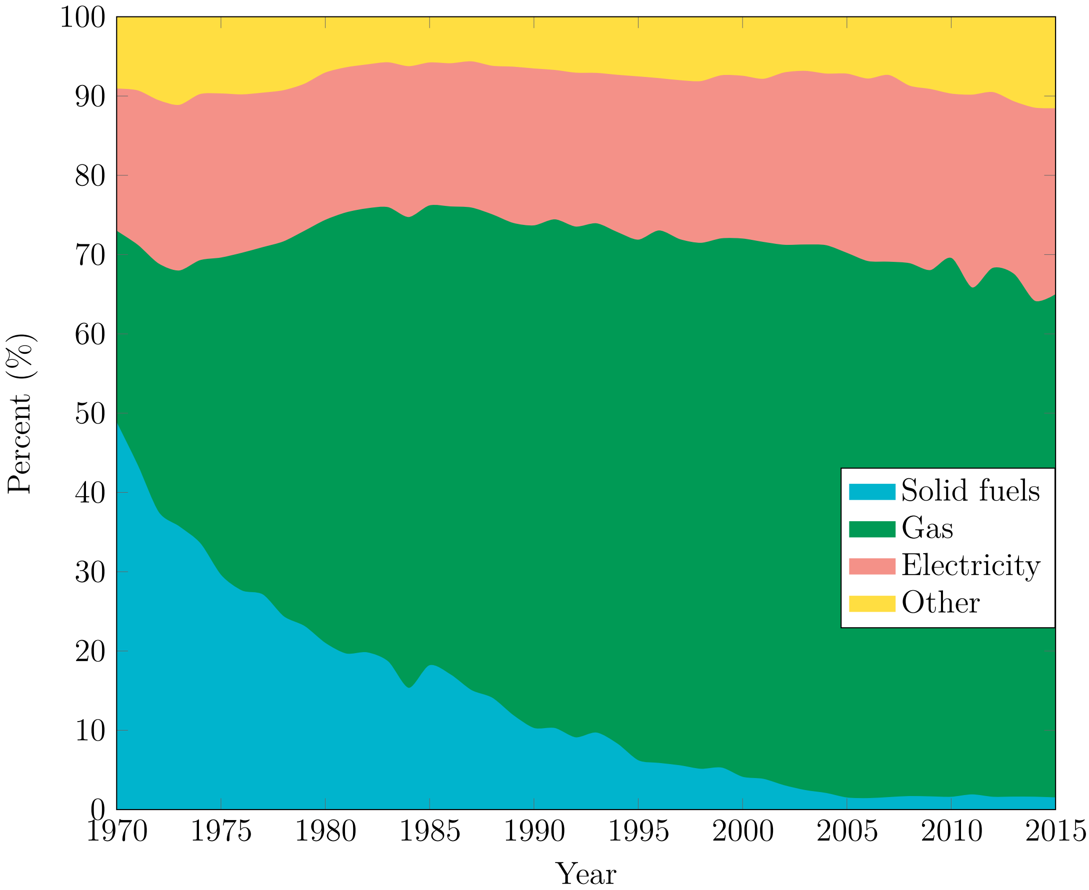


Figure 2.4: Household final energy consumption by fuel [40]

Note: Solid fuels include: coal, coke and other solid fuels; Other include: bioenergy and waste, heat sold, and petroleum

followed closely by energy used for water heating. Space heating is largely dependent on the external temperatures, energy efficiency measures in households and personal preferences. It is directly related to the adequate level of comfort need. Insulation in houses as well as double-glazed windows improve energy efficiency [35]. New homes are constructed using insulation material which leads to energy savings [35, 40]. Water heating satisfies need for adequate level of personal hygiene as well as clean and safe environment. The amount of energy used for this purpose has fallen in the recent years due to reduced heat loss from stored hot water, more efficient heating systems, the move to use combi-boilers rather than boilers and hot water tanks and also greater use of electric showers and dishwashers [35, 45]. Another contributing factor to energy consumption is energy used for food preparation and cooking. This sector is connected to the need for adequate nutritional food. About two-fifths less energy is now used in cooking than was used in 1970 [42]. Some part of these savings have been transferred to domestic appliances, such as new devices like microwaves, sandwich toasters and bread machines, which have replaced traditional ovens and stoves. More-

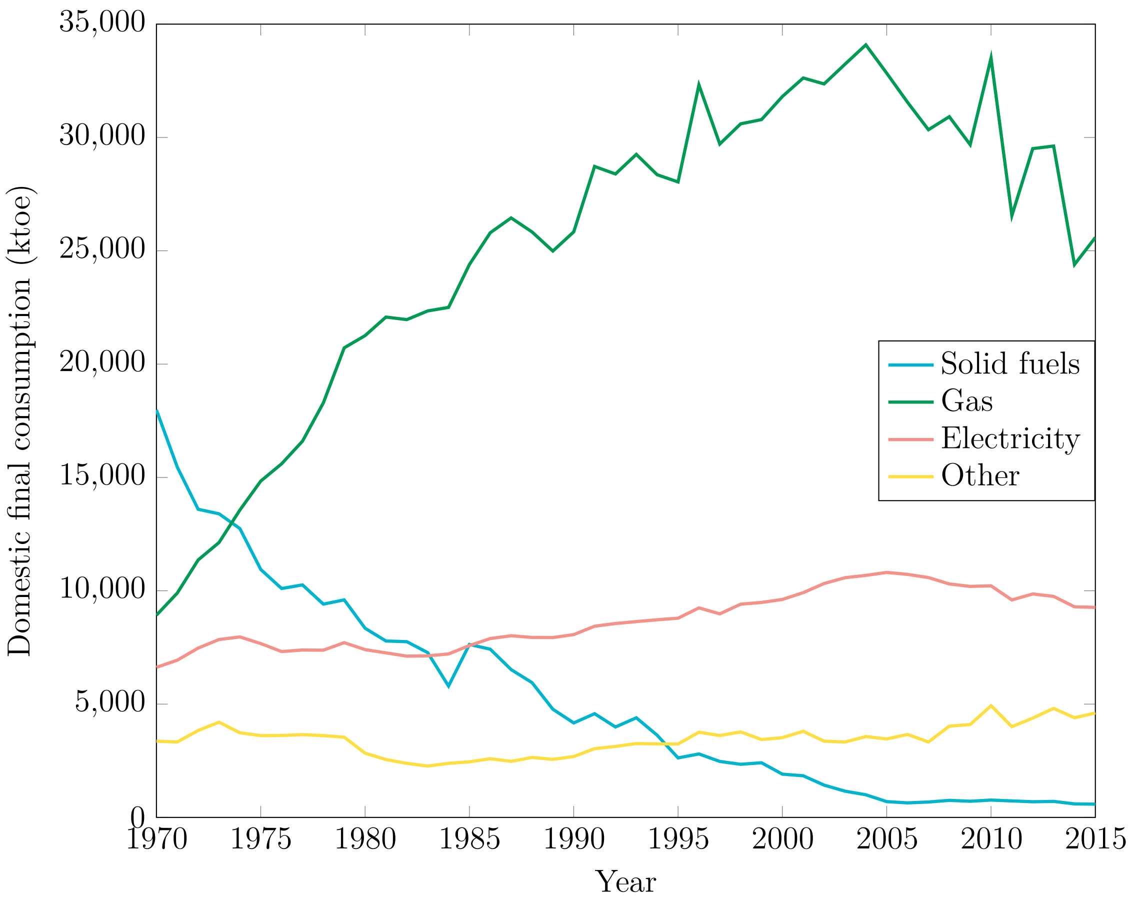


Figure 2.5: Household absolute final energy consumption by fuel [40]

Note: Solid fuels include: coal, coke and other solid fuels; Other include: bioenergy and waste, heat sold, and petroleum

over, people tend to eat out more than they had in the past. It is questionable whether these lifestyle changes have saved energy overall [42, 40]. The number of appliances used for food storage (fridges and freezers) as well as for cooking (electric oven, electric hob, microwave, kettle) has changed over the last 40 years. Moreover, the efficiency of new cold appliances has improved causing the energy consumption to fall. There has been a significant increase in the number and the size of appliances for food storage as well as cooking appliances. Electric hobs or gas stoves, ovens, microwaves and kettles are now commonplace in the UK [40]. About twenty times more energy is now used for dishwashers than it was in 1970. It is caused by the fact, that nowadays dishwashers are present in about 90% of all households [35]. Energy use for lighting accounts for approximately 3% of energy used within households. It is used to satisfy the need for sufficient amount of light. . In 1970 over 93% of bulbs used in households were incandescent lamps. However, since then they have been replaced by energy efficient ones: Light Emitting Diodes (LEDs) and Compact Fluorescent Lamps

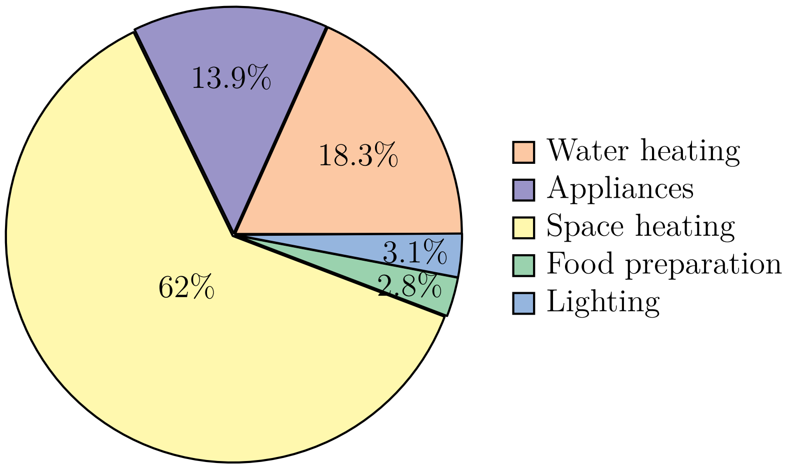


Figure 2.6: Energy end-use in households in 2015 [35]

(CFLs) [52]. The number of consumer electronics devices (such as TV, set top box, DVD/VCR, games consoles) as well as household appliances used for home computing (such as desktops, laptops, monitors, printers, multi-function devices) changed drastically. Nowadays 97 % of all households own at least one TV, 75% at least one computer, and 90% at least one DVD player [53]. These devices can be used to satisfy need for entertainment.

2.3.2 Household water consumption in the UK

Household water consumption accounted for 47% of all water used in UK in 2015 [54]. Several factors influencing water consumption were identified in the literature:

- number of people occupying a household (Table 2.2 [55, 56]);
- type of dwelling [56];
- climatic conditions [42, 57];
- culture traditions, diet, lifestyle [57];
- technical factors such as the efficiency of the appliances used within a household, e.g. washing machines, dishwashers [45, 58, 59, 60, 61];
- presence of garden [55, 56];
- presence of a water meter [62, 63];
- age of household residents [55, 64, 65];
- time of the day, week, year [55, 66];
- leakages [63, 66].

Average water consumption in the UK is estimated at 140 litres per person per day [68, 69].

Table 2.2: Average water consumption in households [67]

Number of people living at home	Water consumption (l/p/d) Low	Average	High
1	123	181	274
2	75	151	186
3	75	124	159
4	75	113	143
5	74	100	124
6	70	91	121

However, according to Gleick the amount of water used can be significantly reduced [57]. He estimated minimum water requirements for human needs (Table 2.3). The range suggested by the author seem quite extreme as cultural, social and personal preferences lean towards water-based systems [57]. Gleick estimated that only 50 litres per person per day is required to satisfy basic human needs, and in his opinion the number he presented is independent of climate, technology or culture. There are possibilities to reduce the amount of water used within a household. They are explained in details in [58, 60, 61, 62].

Table 2.3: Recommended basic water requirements for human needs [57]

Purpose	Recommended Minimum (l/p/d)	Range (l/p/d)
Drinking water	5	2 to 5
Sanitation services	20	0 to over 75
Bathing	15	5 to 70
Cooking and Kitchen	10	10 to 50
Total	50	17 to over 200

Fox et al. classified households according to water demand, see [56]. Their research showed that the relationship between household size and number of occupants is not linear. Moreover, they confirmed Butler's theory that even if there are more occupants in a household, per capita consumption levels are lower. It was shown that properties with more bedrooms had significantly higher water demand [55]. Additionally, the study confirmed that, on average, properties with garden use 152 l/day in summer and 124 l/day in winter more water per property than properties without garden, see [56].

Type of appliances used within a property as well as personal preferences have a large impact on water consumption. Introduction of low volume flush toilets and encouragement to take showers instead of baths have reduced water use within a household [60]. There are many other possibilities to reduce the amount of water that is used, i.e. by fitting water efficient appliances (e.g. low flow taps, low flow showers, low water use washing machines, etc. [58, 60]), or recycling and reusing greywater, or fitting a water meter [62]. Nowadays, more than 40% of British households have a fitted water meter [70]. It helps to control water consumption within a property. On average, water consumption decreases by 10% when water meter is installed and help detecting leaks [62]. Another factor influencing water consumption is demographic structure and was analysed in [64] and [65]. Generally, students have the highest per capita water consumption. It is mostly caused by unmetered properties that they occupy [64].

It is important to realise that water consumption in households varies over time. Depending on the time interval, the consumption might be changing daily. Usually there is a morning peak around 8 am when people are getting ready for work, then moderate mid-day usage lasting till 4 pm, an evening and relatively small late night peak when people are coming back and subdued low night usage until 4 am, see [55]. Also, the consumption is different during the weekdays and the weekend. There are also seasonal changes, for example in the summer water consumption might increase due to flower and garden watering, etc. [66].

Nowadays approximately 4% of that water is used for drinking and cooking, see Figure 2.7. Therefore not all of the water used within a household has to be treated to potable quality. Some of non-potable water needs could be met in an alternative way, for example water from baths, showers and sinks could be recycled and reused for garden watering. Also, rainwater could be harvested and processed [62].

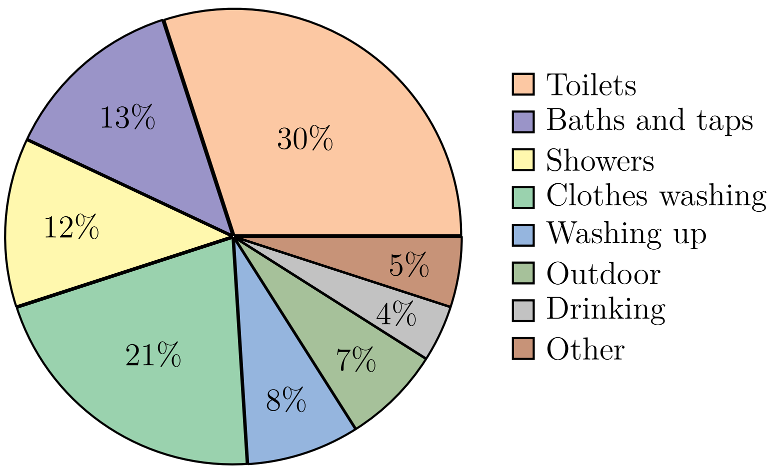


Figure 2.7: Water end-use in households [69]

2.3.3 Waste management in the UK

In 2014 the domestic sector accounted for 13.7% of generated waste. The amount of domestic waste produced and recycled in the recent years in presented in Figure 2.8. The recycling rate fell from 44.9% in 2014 to 44.3% in 2015 despite the government's aim to recycle at least 50% of domestic waste by 2020 [71].

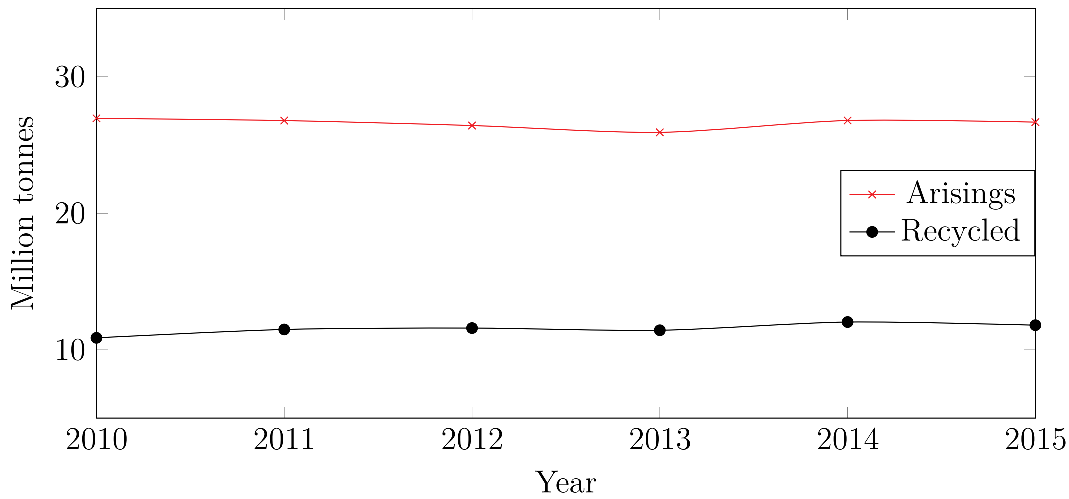


Figure 2.8: Waste from households in the UK [71]

Waste collected from household is divided in the following categories [72]:

- residual waste – collected in bins and black bags, bulky waste and rejects from recycling;
- dry recycling – collected in orange bins and bags;
- food waste – separately collected;
- other organics – green garden waste, compostable waste.

The UK policy on waste collection is taken by the local waste disposal authority, i.e. county council hence it varies across the country.

Households in the UK were responsible for producing 7.33 million tonnes of food waste in 2015 (which is associated with around 15 million tonnes of greenhouse gas emissions), of which 4.4 million tonnes of avoidable food waste [72].

2.3.4 Future demand

Sections 2.3.1 and 2.3.2 contain the summary of energy and water consumption in the UK in the last 45 years. It is estimated that population in the UK will reach 70 million by 2026 [34], with the global population reaching 8.5 billion at the same time [73]. Section 2.3.1 shows that domestic energy consumption is increasing. There are more energy efficient appliances available, but the number of electronic appliances in each household is increasing. If the population projections are correct, energy consumption will also increase. According to the United Nations by 2035 the global energy consumption will increase by 50% compared to the current consumption while water consumption is predicted to increase by 85% by the same year [74]. The fuel mix consumed in household is constantly changing as presented in Figure 2.5. The Department of Energy & Climate Change set a target for 2020 that 15% of all energy in the UK must come from renewable sources [75]. However, according to the World Bank globally 2.5 billion people have unreliable or no access to electricity. At the same time, 2.8 billion people live in areas with high water stress [76]. These numbers suggest the need for infrastructure independent households/communities where some of the energy/water needs can be met locally by using naturally available resources. Additionally, there is a need to minimise waste products by e.g. converting them into energy, extracting water, or converting them into useful fertilizers.

2.4 Sustainability

There are several approaches to defining sustainability. The concept is primarily related to the use of naturally available resources, non-renewable minerals and energy resources. According to Hasna, sustainability refers to a development of all aspects of human life affecting sustenance. Sustainable development according to Allen [6], is the development that is likely to achieve lasting satisfaction of human needs and improvement of the quality of life under conditions that ecosystem and/or species are utilized at levels and in ways that allow them to keep renewing themselves. In 1987 the World Commission on Environment and Development introduced the most widely known definition of sustainable development: "... is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [7]. Additionally, "Sustainable development implies using renewable natural resources in a manner which does not eliminate or degrade them, or otherwise diminish their usefulness for future generations... Sustainable development further implies using non-renewable (exhaustible) mineral resources in a manner which does not unnecessarily preclude easy access to them by future generations... Sustainable development also implies depleting non-renewable energy resources at a slow enough rate so as to ensure the high probability of an orderly society transition to renewable energy sources" [77, p.37]. However, there are many others definitions in the literature, see e.g. [78, 79, 80, 81]. According to a dictionary the phrase *sustain* means "allow to remain in a place or position or maintain a property or feature", "provide with nourishment" and "supply with necessities and support" [1].

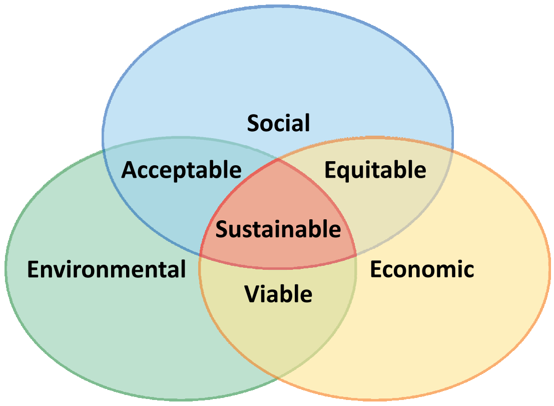


Figure 2.9: Three pillars of sustainability [73]

The definition suggested by the World Commission on Environment and Development is the one adapted by the United Nations [73]. They recognise there are three pillars necessary for sustainable development (Figure 2.9). These three aspects are linked together and are crucial in achieving sustainability. This interconnection was highlighted by the UN in 2000 by establishing eight Millennium Development Goals (MDGs) [82]. The participating countries were challenged with reaching the goal within 15 years [83]. They were considered largely successful as the objectives were mostly met [82, 84]:

1. Eradicate Extreme Hunger and Poverty

   Target: Halve the proportion of people with income less than a dollar per day (between 1990 and 2015).

   Outcome: The target has been met and it reached 57% (compared to the 1990 baseline).

   Target: Achieve full and productive employment and decent work for all, including women and young people.

   Outcome: The target has not been met as the global economic crisis impacted the labour market.

   Target: Halve the proportion of people who suffer from hunger (between 1990 and 2015).

   Outcome: The target was closely missed, as the rate of undernourished people in 2015 (compared to the 1990 baseline) reached 47%.

2. Achieve Universal Primary Education

Target: Achieve 100% enrolment and completion of primary school education

Outcome: The target has been missed as the primary school enrolment reached 91% in developing countries.

3. Promote Gender Equality and Empower Women

Target: Eliminate gender disparity in schools.

Outcome: The target has been achieved. There was a significant increase in the number of girls in schools. Nowadays, for every 100 boys 103 girls are enrolled. The number of women in parliament has doubled since 1995 and 90% of countries have more women in parliament compared with that date. The rate of women employed outside the agricultural sector has risen to 41% compared to 30% in 1990.

4. Reduce Child Mortality

Target: Drop of two-thirds in the under-five mortality rate (between 1990 and 2015).

Outcome: The target has not been met. However, there was a significant drop in the under-five mortality rate: from 90 (in 1990) to 43 (in 2015) deaths per 1,000 live births.

5. Improve Maternal Health

Target: Drop of three-quarters in the the maternal mortality ratio (between 1990 and 2015).

Outcome: The target has not been met, but the maternal mortality rate has declined by 55%.

Target: Achieve, universal access to reproductive health (by 2015).

Outcome: The goal has not been met. However, contraceptive prevalence among women aged 15 to 49, increased from 55% in 1990 worldwide to 64% in 2015.

6. Combat HIV/AIDS, Malaria and other diseases

Target: Have halted by 2015 and begun to reverse the spread of HIV/AIDS.

Outcome: The goal has not been met. However, the number of HIV infections fell by 40%

Target: Achieve, universal access to treatment for HIV/AIDS (by 2010).

Outcome: There was an increase in the number of people living with HIV that were receiving antiretroviral therapy - from 0.8 million in 2003 to 13.6 million in mid 2014.

Target: Have halted by 2015 and begun to reverse the incidence of malaria and other major diseases.

Outcome: It has been reported by the UN that over 6.2 million deaths due to malaria has been averted between 2000 and 2015. The incidence of malaria has declined by about 37% between 2000 and 2015, while the mortality rate due to other major diseases has dropped by 58% between 2000 and 2015.

7. Ensure Environmental Sustainability

Target: Integrating the principles of sustainable development into policies to reverse the loss of environmental resources.

Outcome: The target has been partially met. The positive aspects are that there was a decrease in deforestation and increase in afforestation and ozone-depleting substances have been eliminated bt 98%, which will enable the ozone layer to recover. The negatives are: greenhouse gas emissions are rising (by more than 50% since 1990), the fish-stocks are depleting due to overexploitation of marine fisheries and water scarcity is affecting more that 40% of the population and is expected to increase.

Target: Reduce biodiversity loss, achieving, a significant reduction in the rate of loss (by 2010).

Outcome: There was a substantial increase in globally protected areas such as terrestrial or marine areas. This, in turn, will help to prevent biodiversity losses.

Target: Reduce by half the proportion of global population that is lacking access to safe drinking water and basic sanitation.

Outcome: The proportion of population using an improved drinking source has risen to 91% in 2015. Additionally, the proportion of population using improved sanitation facilities increased to 68%. Moreover, 147 countries met the drinking water target while 95 met the sanitation target. 77 countries met both of these targets.

Target: Achieve a significant improvement in the lives of at least 100 million slum dwellers (by 2020).

Outcome: Population living in slums has decreased in almost all regions. However, the proportion of urban population living in slums is still high (almost 30%).

8. Develop a Global Partnership for Development - The target was met as there was an increase by 66% (between 2000 and 2014) in official development

assistance from developed countries. Additionally, the duty-free import rate from developing to developed countries has risen to 79%.

The MDGs show the importance of the integration of the three pillars of sustainability. The environmental pillar is paramount in facing the challenges, e.g. water scarcity, food insecurity, climate change and natural disasters as well as poverty eradication and socioeconomic development. Therefore, the successor of MDGs must reflect the links between social, economic and environmental aspects and must reinforce the environmental pillar [82]. Therefore, in June 2012 during Rio+20 the Open Working Group was established to develop new sustainable development agenda to follow the MDGs [85]. After more than a year of negotiations, recommendations for the 17 Sustainable Development Goals (SDGs) were proposed (Figure 2.10). They are a key component of the 2030 Agenda for Sustainable Development [15].

Figure 2.10: Sustainable Development Goals [15]

The 17 SDGs with their 169 targets were designed to complete the MDGs targets and go beyond them. They also emphasize the importance of balance between the social, economic and environmental pillars. However, their main goal is to create a sustainable future for the people, planet, prosperity, peace and partnership [15]. They propose a guidance for global population to prosper

[86, 87]. Each of the 169 targets has a set of associated indicators to assess how effectively it is achieving its goals. Indicators in general are an useful tool for many tasks:

- Evaluating the current state of sustainability in cities [15, 88];
- Identifying areas where actions might be needed [89];
- Informing stakeholders about the current situation in the city or country [88];
- Influencing policy makers [90, 91];
- Communicating with citizens about activities undertaken by city councils [90].

Research presented in this thesis is connected to SDG 11: "Make cities and human settlements inclusive, safe, resilient and sustainable" [92]. This goal is focused on assuring that by 2030 [92]:

- Everybody living in urban areas will have access to basic services as well as safe and affordable housing.
- The proportion of urban population living in slums will be reduced.
- Transport system will be sustainable, safe, affordable and accessible especially for those in vulnerable situations, e.g. older persons, women and children, persons with disabilities.
- Settlement planning and management will be done in a participatory, integrated and sustainable way.
- Efforts to protect and preserve the world's natural and cultural heritage will be strengthened.
- The number of people affected by disasters as well as economic losses due to disasters will be significantly reduced.
- The environmental impact of cities will be reduced.
- Access to safe green and public spaces will be provided to all, especially for those in vulnerable situations, e.g. older persons, women and children, persons with disabilities.

The research is also connected to SDG 6: "Ensure availability and sustainable management of water and sanitation for all" [92]. It is analysing ways of reducing water consumption as well as reducing the amount of freshwater withdraw by proposing recycling and alternative sources of water.

Sustainability has many dimensions, but the main focus in this thesis is on sustainable communities and households. In the following Section 2.4.1 and Section 2.4.2 these two aspects will be considered.

2.4.1 Sustainable Communities

The term sustainable communities refers to communities that are promoting sustainability and sustainable development. They include new-built as well as the existing communities that want to improve. The Sustainable Communities Plan from 2003 defines sustainable community as places protecting the environment, care about their residents contributing to a high quality of life [93]. They also are planned, built and run in such a way, that not only the needs of existing residents are satisfied, but also the needs of the future ones will be met. According to Egan such communities have eight main characteristics [94]. They are often represented in a form of a wheel (see Figure 2.11).

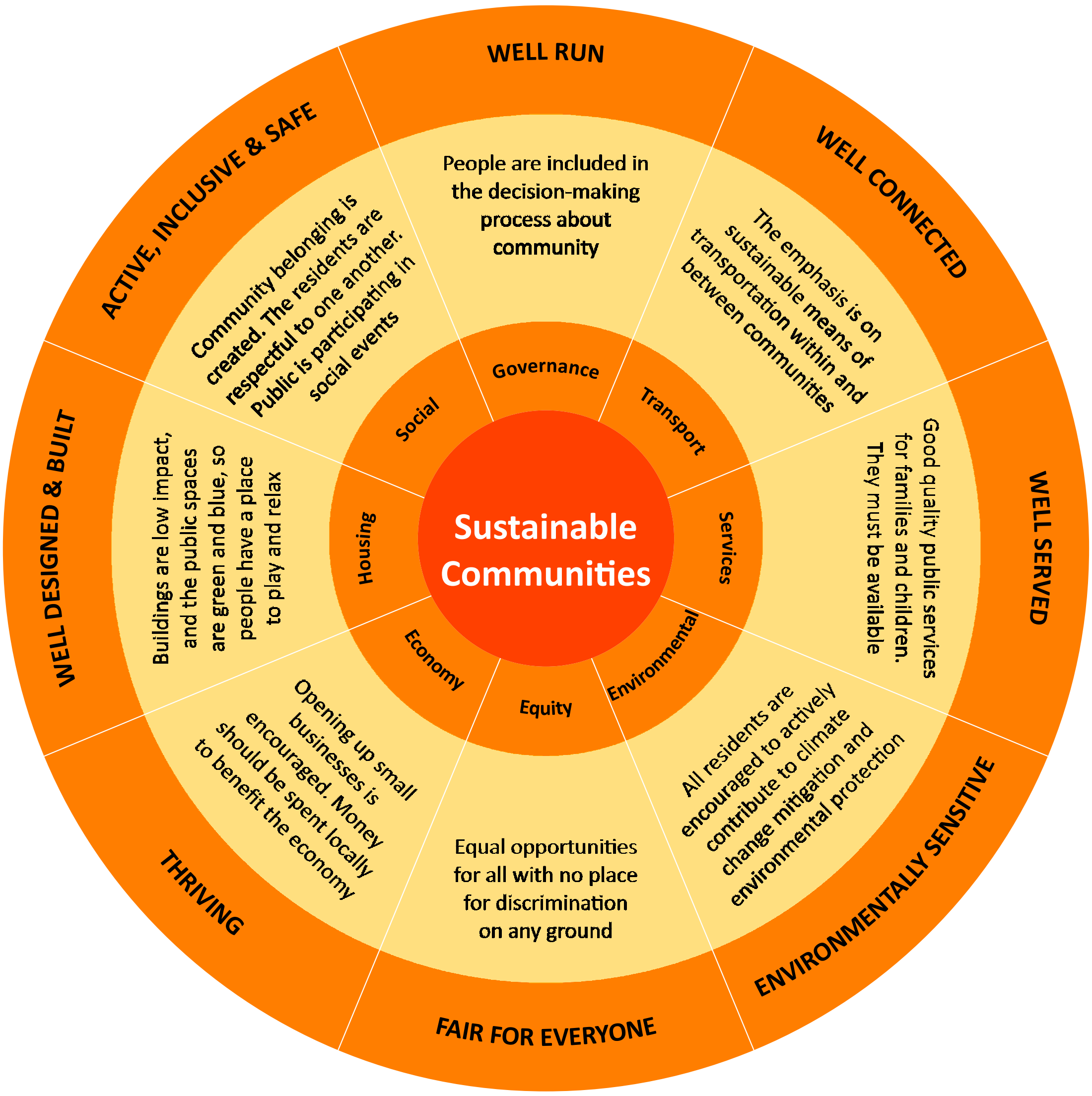


Figure 2.11: Sustainable Communities Wheel [94]

These characteristics provide a vision of a community where the environmental aspects are a key to prosperity of current and future generations. They also provide a balance between the three pillars of sustainable development (see Figure 2.9).

In 2007 The Sustainable Communities Act was introduced by the UK Government [95]. It promotes sustainability of local communities. It allows people to recognize what is the best way for their community to be more sustainable and provides opportunities to submit proposals that will help them achieve their goals. There are many communities in the UK that are trying to become more sustainable, e.g.:

- Slough community near London [96]. In 2008 the council set up 20 year plan with five priorities: to create a diverse community, to give the residents a chance for better and healthier lifestyle choices, to reduce crime and create a safe environment, to lower carbon emissions as well as provide more green places, and, finally, to sort out an economic approach to ensure prosperity for all [96].
- Solihull community near Birmingham [97]. In 2016 they delivered a *Green Prospectus* that was built on their existing *Sustainability Strategy*. In 2017 a refreshed *Greener Prospectus* was delivered that addressed the SDG. The city council provided a clear short and long term strategies for greening the economy, buildings and their efficiency, energy and resources, transportation and mobility, natural capital and adaptation, and communication education and engagement.
- Lammas - Tir y Gafel - a new-built eco village in North Pembrokeshire in Wales [98]. All buildings must be zero-carbon in construction and use, according to guidelines on low-impact homes [99]. The occupants must meet their basic needs from land-based livelihoods within 5 years. They are working towards one-planet footprint. The Global Footprint Network estimates that at the moment to sustain the global population in the long term need one and a half planets is required [100]. Additionally, if everyone lived in the same way as people in the average developed nation, at least three planets would be needed to sustain the population. In this community people are growing their own food, breeding animals, the electricity comes from the natural resources, rainwater is harvested and processed, waste water is treated and returned to landfill. 75% of their earnings has to come from the land. This concept is interesting and definitely environmentally friendly, but seems to be limited to a specific group of people. The community is a part of “Living In The Future” project [101].
- Springhill Cohousing near the centre of Stroud in Gloucestershire [102]. The idea of cohousing started in 1960’s in Denmark [103]. The project started in 2000 and now consist of 34 housing units and a common house where

the community meets. The cars are left on the periphery of the community to create safer and cleaner atmosphere. Walking and cycling is the main mode of transport followed by car-sharing schemes.

– Hockerton Housing Project near Southwell [104] is a cohousing scheme. The houses are earth-sheltered and built to eliminate the space heating needs. The residents generate their electricity by sharing two wind turbines and solar panels. There is also an energy monitoring system in place which enables the residents to see their own as well as their neighbours consumption. As the billing is collective it prompts low electricity usage. Water is harvested, treated and reused. Additionally, the residents are in about two-third self-sufficient in food (eggs, fruits and vegetables).

In all of these examples the same approach is transparent: a push for low or zero energy housing, use of natural resources, locally grown food and better waste management. Sustainable communities should be build on the three pillars (Table 2.4).

Table 2.4: Characteristics of sustainable communities [94, 105]

Pillar	Characteristics
Environmental	efficient water and energy use
	minimise waste production
	maximise waste recycling and reuse
	protect natural environment
	minimise pollution
	emphasis on cycling and walking
	support car sharing schemes
	use of natural resources
	locally grown food
	low or zero energy housing
	design includes green and blue spaces
Social	public participation in social life
	designed to bring people together
	respectful and inclusive
	meeting human needs locally
	encouraging public participation in decision making
Economic	support local small business owners
	encouraging spending money locally
	value volunteering
	create job opportunities within the community

2.4.2 Sustainable Houses

Sustainable buildings/houses are a key part of sustainable communities. There is a discussion on how sustainability of a particular building should be measured [106, 107]. Berardi proposed that not only the building itself should be analysed, but also that the surrounding environment must be considered. Therefore, it is essential to assess the naturally available resources in the imminent area as well as the impact that the building will have on its surroundings. Additionally, by considering the three pillars of sustainability, the house should be close to public transport and in a proximity of potential employment [108]. A sustainable house should contribute to the characteristics of sustainable communities (Table 2.4). Therefore, from the technical standpoint, a sustainable house should [105, 108, 109]:

- be constructed using local renewable materials while minimising waste,
- be equipped with energy and water saving appliances,
- utilize naturally available resources,
- be constructed to enable water recycling and reuse,
- have low environmental impact,
- be embedded in the natural environment,
- create opportunity to grow food locally,
- be constructed to last with low exploitation costs,
- be safe and secure.

2.5 General approaches for assessing sustainability

There are various ways in which sustainability of a household, community or a city can be assessed. There is a nexus approach that is investigating dependencies between different aspects such as water, energy, environment, food or land use and is discussed in Section 2.5.1. The approach to consider cities and households as a metaphor for a living organism and study their metabolism is introduced in Section 2.5.2.

2.5.1 Nexus approach

Extensive research has been conducted in separate aspects of utility–service provision and its sustainability. For many years scientists and engineers have been working on improvements of ways to deliver utility products to households, as well as removing unnecessary and/or unwanted products. Today each utility product such as water, gas, electricity, etc. is delivered to end-users via separate infrastructure [26, 110, 111]. This leads to problems not only with installation, managing or maintenance, but also raises questions, such as: which option is the best to heat a house? Is there any cheaper solution for waste removal? Are there any more sustainable or more environmentally friendly solutions? etc. Moreover, the utility companies are looking for new solutions to reduce the cost and improve efficiency of providing services to customers. However, the research direction is shifting into the links between various aspects. Makropoulos and Butler discussed the connection between water, energy and land uses [112]. They identified devices and technologies that might be useful to reduce water consumption within a household, but emphasize the fact that those devices will consume more energy as well as space than standard solutions. They emphasize that there is a direct link between energy, water and land use. According to the authors, there is an equilibrium point that is connected to technologies available at any given time. That is why any water saving solutions will either increase energy consumption or land use. Gleick was one of the first that start discussion on water and energy dependency [113]. In the last decade research in this topic increased and is now referred to as the "water–energy nexus". Different dimensions of the interconnections are investigated. Similarly to sustainable development, environmental, social and economic are amongst them, but also political and technological dimensions are considered. Additionally, comprehensive research was conducted on the impact of water and energy on different industries, on water sector, or on domestic users, and how water is dependant on energy and vice versa [114, 115].

Lately, a third aspect was added to deliberation: food. The trio is sometimes referred to as the "resource trilemma" [116, p.1]. It is increasingly being recognised by policy makers especially to minimise the trade-offs of cross-sectoral impacts [116, 117] An interesting approach is presented by Hussien et al. where the water-energy-food nexus is considered at a household scale [118]. The relationship between water, energy and food parameters was mapped and a modelling approach was developed to present the impact of family size, diet, user behaviour and others on water, energy and food consumption [118].

Naturally, any processes will have impact on the environment, e.g. wastewater treatment process and associated greenhouse gas emissions [119]. Therefore, it is another branch of research that is being acknowledged: water-energy-environment nexus. Some researchers investigated urban water systems and their environmental impacts [120], while others focused on their isolated aspects [121]. Additionally, some researchers found that the attitude of consumers plays an important role in water and energy use as well as carbon emissions [122].

2.5.2 Metabolism approach

Urban metabolism was first discussed by Karl Marx in 1883 to describe the material and energy flows between nature and society [123, 124]. The term was later used by Wolman to analyse an hypothetical city in United States [126]. Researchers started wondering whether it is possible for cities to mimic the same processes in natural systems thus using gained insight from these systems. Therefore, a loose metaphor between cities and organisms was made [127, 128]. On the one hand resources can be perceived as nutrients that need to be delivered to the city. On the other hand, consumption of these resources generates waste or pollutants that can be viewed as metabolites which should be captured to be either reused or removed. If the city cannot cope with these processes it can face ecological damage, environmental pollution which threaten the city's sustainable development. It can be summarised that urban metabolism focuses on the sources and consumption of resources, and on their flow within the system as well as on the emissions, recycling and treatment of wastes [124]. Therefore, urban metabolism considers the inflows of water, materials and energy resources and the outflows of emissions and wastes as well as the retention of materials in the environment and infrastructure [127].

However, the metaphor between cities and organisms was criticised by some researchers. Bohle emphasised that the metaphor should be constrained by the natural laws that govern social processes and structures [129]. According to Fischer-Kowalski the concept of metabolism is a way to emphasize the energy and material flows and the associated processes in a socioeconomic system [130]. It seems that it would be more appropriate to compare a city to an ecosystem rather than to an individual organism as cities represent systems combining multiple organisms, including humans, animals, and plants [131, 132]. This approach enabled a more practical use of the metabolic metaphor. The roles of the biological organisms in an ecosystem could be used to define the relationships between components of the system. Therefore, the consumer, manufacturing, and waste disposal infrastructures of a city can be corresponding to the consumers, producers, and decomposers in a natural system [133]. Thus, it became possible to use knowledge and tools from ecosystem research to simulate energy flows and material cycling to reduce possible environmental pressures [134]. This metaphor allows the improvement of the processes of socioeconomic systems using the tools developed during research on ecological systems and their metabolic processes [128].

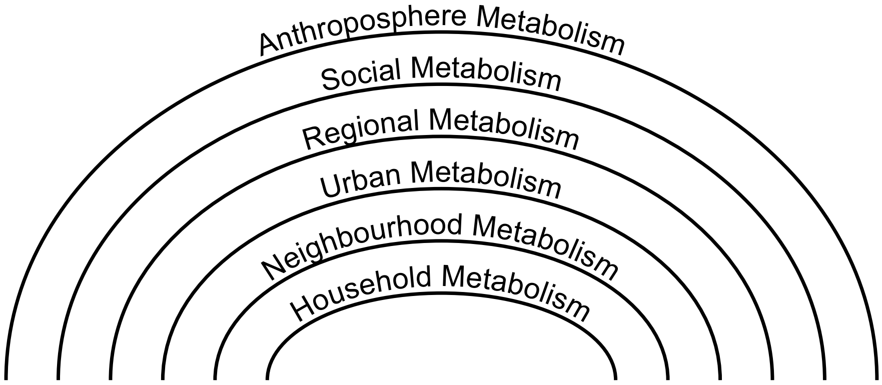


Figure 2.12: The multiple scales of urban metabolism [128].

When analysing any system a clear definition of its boundaries needs to be established. There is a certain hierarchy in an urban system (Figure 2.12). A household is a part of a community, which is a part of a city, that is a part of a country, etc. However, it is difficult to define a scope of an urban system, because there is no obvious boundary between humans and nature [128, 135]. A city can extend beyond the built-up area including the rural areas that surround the urban area [133]. Therefore, for practical reasons (e.g. data collection) the system boundary can follow political boundaries of a city. It might be also useful to analyse first smaller components within a city, e.g. through the study of neighbourhood [136] or household metabolism [137, 138, 139].

The term household metabolism refers to both the supply of resources that are indirectly required in households, e.g. energy and water needed to manufacture goods, as well as the demand for resources that are directly required in households, e.g. water for drinking and cooking [137, 138]. The household metabolism concept is presented in Figure 2.13 with physical inputs and outputs related to household consumption. These physical flows are numbered as follows:

1. Indirect water and energy consumption, i.e. water and energy embodied in consumer goods.
2. Direct water and energy consumption, i.e. water used for drinking, cooking, washing, etc. and energy used for heating, cooking, lightning, etc.
3. CO_2 emissions related to both direct and indirect energy consumption.
4. Solid waste flows [139].

Household metabolism was addressed by the HOMES (Household Metabolism Effectively Sustainable) project. The aim of the project was to diagnose and evaluate household metabolism in the Netherlands [139, 140]. There is also an increasing number of studies discussing the sustainability and related environmental consequences of household consumption [140, 141, 142, 143].

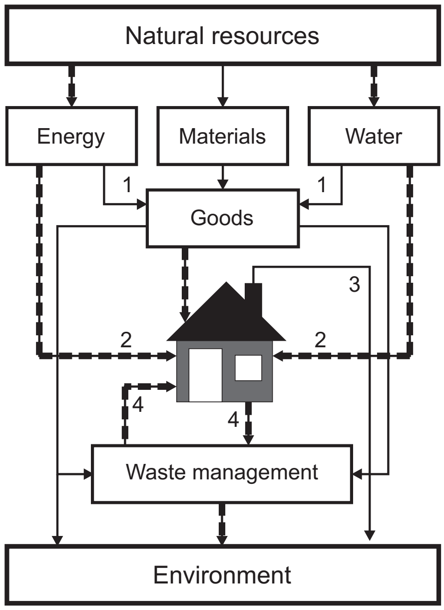


Figure 2.13: The household metabolism concept [139].

Utility–service provision can be considered as a part of the household metabolism concept as its main focus is the direct product consumption in the household (bold lines in Figure 2.13) and is discussed in Chapter 3.

Not only the boundaries are important, but also the the perspective that is taken when analysing urban metabolism (Figure 2.14). Three different approaches can be adapted [127, 144]:

(a) Household consumption based approach (Figure 2.14.a) - the system boundaries are placed around residential premises in a city and the environmental impacts associated with flows to the household are analysed regardless if they originate inside or outside the city. It captures economy-wide impacts of consumption and lifestyles. They are relevant for policy makers focused on climate mitigation. The methods most widely used in this approach are:

- the input-output analysis (IOA) that assesses both direct and indirect water and energy consumption, carbon and ecological footprinting and greenhouse gas (GHG) accounting [144, 145, 146, 147].
- the life-cycle analysis (LCA) that considers each product from 'cradle to grave', i.e. from material source to final disposal [127]. This approach enables a full assessment of a flow, especially the environmental impacts such as GHG emissions.
- hybrid input-output life-cycle analysis (IO-LCA) that offers a holistic approach to assessing GHG emissions from the consumption perspective [144, 148].

(b) Urban metabolism approach (Figure 2.14.b) - a production-consumption approach that includes impacts both from production in the city and associated with net imports of energy and materials. The main method used is material flow analysis (MFA) that quantifies the inputs and outputs of a process [149, 150]. This method can be applied across different scales: household, neighbourhoods, communities, cities, etc. [144].

(c) Complex system approach (Figure 2.14.c) - attempts to capture the dynamics within cities at various scales. However, it is not a mixture of above mentioned approaches. The aim is to capture system interactions and feedbacks that can be used for urban planning [151]. There is no general way of defining spatial boundaries in this approach [144].

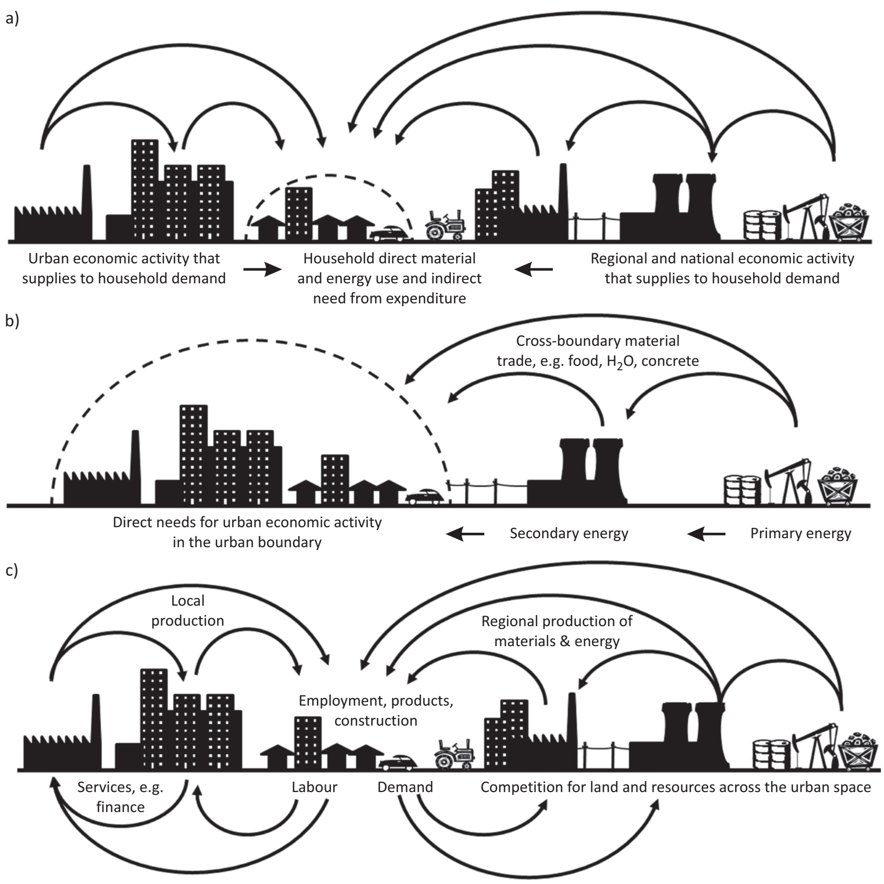


Figure 2.14: Depiction of material, energy and information flows in three approaches, based on: a) consumption; b) urban metabolism; c) complex systems [144].

These approaches offer evaluation of the current situation with regards to consumption and environmental impact, but also offer the possibility of simulating future scenarios [144].

2.6 All in One Project vignettes

The main aim of the "All in One" project was to answer the question: "Can a single utility product and/or infrastructure be sufficient to supply all household services and products that end users might want?" [26]. The aim of the project was to envisage scenarios where utility–service provision is replaced by single product or infrastructure 100 years in the future [21]. The main contribution of the team from De Montfort University was a simulation system that analyses the technical/technological and economic feasibility of such scenarios. The main outcome of the project was a set of so-called "vignettes" - futuristic scenarios of utility–service provision. The scenarios were developed by the researchers in the project based on personal preferences towards "the one", and were improved by exchanging views and opinions at workshops, conferences, meetings, etc. They are a valuable tool to provide useful insights into the challenges that might occur [152]. These types of scenarios are not necessarily built on predictions or forecasts. However, they offer possible visions of the future [153]. The technical feasibility analysis was undertaken for each of them and gaps in science were identified as well as yet-to-be-invented technologies or devices. The developed vignettes are:

- "The Blood of the City", Cranfield University - inspired by the human body, where "the one" is water delivery infrastructure. Authors propose that water and energy could be supplied to a household in a single pipeline. As energy and water separation process might prove to be challenging, it is suggested to use an alternative energy delivery option: bio/fossil fuels or solid/liquid-substrate hydrogen carriers, dissolved or suspended in water. However, local wastewater treatment is necessary, as transporting clean water and wastewater in one pipeline would prove to be problematic and unsanitary. This vignette is described in detail in [21, 154, 155].
- "The Intertubes", University of Sheffield - inspired by "Foodtubes" proposal for a underground network of tunnels carrying a variety of specialist capsule types [156]. Similarly to the previous vignette, "the one" is an infrastructure of underground tunnels. The network would have terminals at supermarkets, schools, offices, recycling centres, etc. The greatest obstacles are not technological but socio-political and economical. The technology exists today, but people are reluctant when it comes to changing their habits [21].
- "The Solar Globe", University of Sheffield - proposes that "the one" is solar energy. It proposes two stages: in the first to maximise the use of photovoltaic and other solar capture systems to convert solar radiation to electricity. The second stage involves building a ring of photovoltaic panels

around the lunar equator. It would generate energy continuously unaffected by terrestrial problems such as earthquakes, bad weather, etc. With an unlimited supply of energy it would be possible to create enough electricity and water for everybody. The main technical and economic feasibility barrier is placing the ring around the moon [26].

– "Subterranea", Cranfield University - is a very pessimistic vision of 2111, when average global temperatures have risen by 13°C resulting in a rise in sea levels by eleven metres. Authors analyse subterranean and sub-aquatic systems as living underwater or underground as the only option to survive the new climatic conditions. It proposes to extend heating, ventilation and air conditioning system to include water and electricity transmissions to provide necessary services, see [21].
– "A methodology for developing utility scenarios", De Montfort University - instead of predicting a particular path into the future we proposed a systematic approach which facilitates generating scenarios for future utility provision and illustrates this approach with two case studies: a community in Scotland and a community in Spain, see [24]. The former community uses electricity as "the one" while the latter uses water. These two case studies are examined using developed simulation system. The case study presented in Chapter 5 is built on these two examples.

The development of the simulation system is described in Chapter 3. Contributions of each of the project partners to the development of the simulation system are specified in Section 3.7.

Chapter 3

Modelling approach

3.1 Introduction

The initial modelling approach adapted in this research was proposed by the researchers from De Montfort University and the author in the "All in One" project as a tool to evaluate the feasibility of futuristic scenarios. There are many predictions about how the future will look like, but as Prof. Ulanicki said: "If one person predicts [the] future he/she is most likely wrong, if one million people predict the future one person among them is most likely to be right but we don't know who" [24, p. 1]. Future utility–service provision is associated with risks and uncertainties [157]. Therefore, proposing a systematic approach via a simulation model to assess the feasibility of a solution might give an insight into its adaptability into the specific situations. Developing models have many advantages, such as:

– Allows to provide simplified representation of a problem [158].
– Allows simulation and in-depth analysis of the considered problem.
– Can be used to identify a potential future scenario.
– Allows explanation and improvement of the tested phenomenon [159].
– Can lead to financial savings.

The first step in developing a model is identification and clarification of the problem to be solved [160]. In order to do so, the problem must be analysed and decomposed, to understand what parameters and variables are influencing the system, what its behaviour is, and what outputs are produced. This is an important step as if the problem is not correctly identified, the analysis and results will most likely be incorrect. In the next step a clear definition of the problem must be formulated. It must include assumptions, outcomes, constraints and limitations, information about parameters and variables involved in the problem. Based on these two steps, the mathematical model can be developed. It should represent the important features of the problem in a clear and easy to interpret way. The models are usually developed to represent specific aspects of a real-world problem and they tend not to include the features that are not relevant to this specific problem [160, 161]. Often, certain assumptions and approximations are made in order to build a model. There are many characteristics that a mathematical model should follow, such as [160, 161, 162]:

- Realism – Models should be as realistic as possible, but may have certain simplifications that will still allow to understand mechanisms and relationships of the investigated phenomenon [161, 162].
- Simplicity – Models should be also simple, so they can be understandable and able to be simulated.
- Robustness – Small changes to input parameters should slightly change the behaviour of the model [160, 162].
- Accuracy – Produces results that are close to real observed values.
- Adaptiveness – The model should be able to be adapted to any changes to the real world problem that is representing [160].

Once the model has been developed, it must be solved and tested. It ensures that the assumptions of the model are correct and whether the model provides answers to the problem. Usually, the model is validated on a smaller sample that is representative enough to check the model's behaviour. Based on this test, the model itself or the problem definition might be re-visited to improve the accuracy or performance the developed model. It is also advisable to conduct sensitivity analysis of the model to check how small changes to parameters influence the behaviour of the model. The process of constructing a model requires constant validation and critical analysis. Obtained solutions must be compared with available observations or data. Once the accuracy and robustness is adequate to the established criteria, the model can be accepted. It can be used then to test hypothesis and draw conclusions [160, 161, 162].

3.2 Utility–service provision model

The idea behind this approach is to provide a simple, yet realistic reflection of processes that occur within households or communities. In order to formalise the approach household/communities are considered as an input-output system as presented in Figure 3.1. Some products can be delivered via separate infrastructures from utilities, while others can be acquired from local natural resources.

The potential for recycling products is indicated by green arrows, while red arrows show waste products, i.e. products that cannot be re-used in a particular situation, hence need to be removed from the system. Additionally, there are certain human needs that are satisfied by the provision of products to households. These needs were identified and divided into services that are necessary to satisfy them. In order to do so, certain devices are required. Moreover, devices are also necessary to transform some products into other, usually more useful, products.

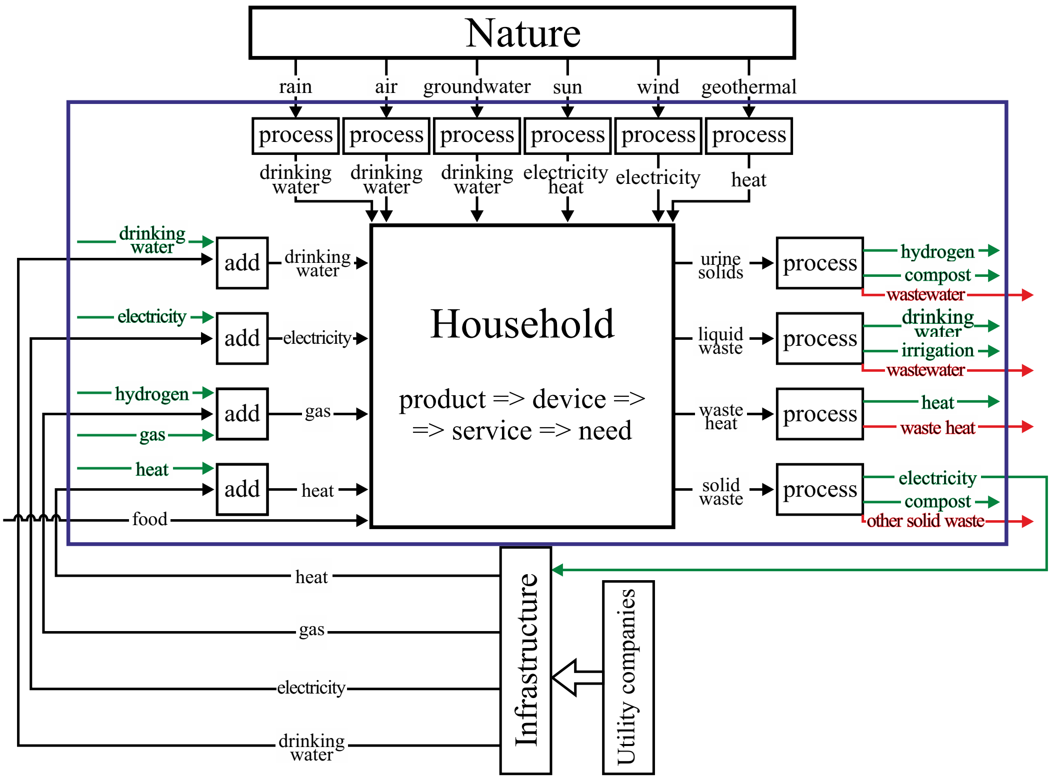


Figure 3.1: Conceptualisation of a household

The conceptualisation presented in Figure 3.1 can be also extended to communities. In this thesis the emphasis is placed on households. In order to facilitate this distinction, some of the devices are tagged as only applicable for communities, e.g. a full scale wind turbine would not be suitable for a single household use, but at least for a cluster of houses.

3.2.1 Model components

The simulation system is composed of the following blocks: an interface to define service-provision problem (explained in Section 3.4), an interface to define candidate solutions (described in Section 3.5), a computational engine to analyse the feasibility of solutions (Section 3.6) and an XML database (Section 3.3).

Both interfaces and the computational engine are developed in C# and .NET 4.0, while the XML database is implemented using eXist-db, an open source native XML database system. The purpose of the XML database is to store information about products, devices, technologies, services and needs, which are used to define utility–service provision problems and candidate solutions using corresponding interfaces. In Section 3.7 the evolution of the modelling approach post the "All in One" project is summarized.

The dependencies between each of the components of the utility–service provision approach are presented in Figure 3.2.

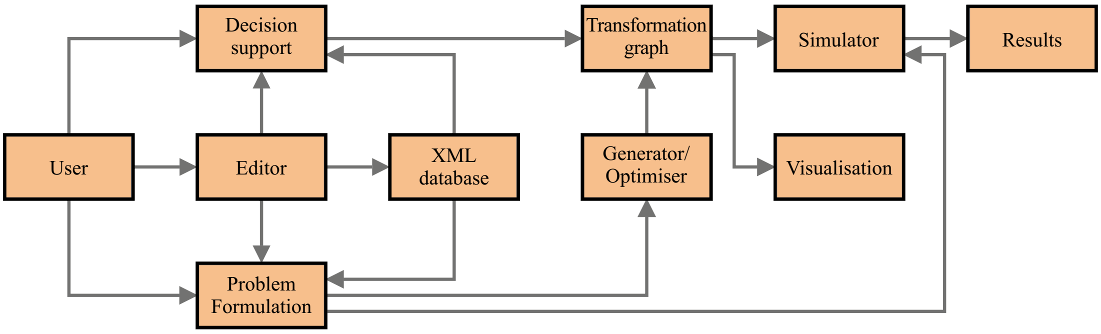


Figure 3.2: Utility–service provision model

A general approach to solve an utility–service provision problem in this model follows these steps:

- Formulate the problem that needs to be solved using information stored in the database. An interface to do so is embedded in the XML Database Content Editor.
- Generate a set of candidate solutions (transformation graphs) using the simulator or define a candidate solution using the decision support system also embedded in the XML Database Content Editor.
- Assess the feasibility of solution(s) using the simulation system.
- Generate result files with mass balances of all products and services for all transformation graphs.
- Visualise the results.

In the modelling approach two different graph representations are used. Firstly, directed standard graphs are used to represent transformation graphs - the candidate solutions. In this representation the nodes represent devices, services and storages associated to each of the products while the edges are product or service carriers. This is further explained in Section 3.5. Secondly, directed hypergraphs are used to represent the entire content of the database in a form of Mastergraph. The second representation was adopted as devices usually connect more than two nodes. Additionally, for the purpose of automatic searches, the nodes and edges (or hyperedges) play the opposite role to the one in transformation graphs, i.e. the edges represent devices and the nodes represent products and services. This inversion helps to analyse the system under investigation as well as search for the shortest paths between products and products/services. The second representation is explained in Section 4.3.

3.2.2 Formal description of utility–service provision problem

The utility–service provision problem can be described in a mathematical format:

Parameters:

T the simulation horizon, $T \in \mathbb{N}$

t a time step, $t = 1, \ldots, T$

up_i a product, $i = 1, \ldots, K$

$proh_i$ a prohibited product, $i = 1, \ldots, L$

d_i a device, $i = 1, \ldots, N$

mt_{d_i} maximum throughput of a device d_i, $i = 1, \ldots, N$

r_{d_i} operation ratio of a device d_i, $i = 1, \ldots, N$

s_i service, $i = 1, \ldots, M$

$sdem_{it}$ service demand at each time step, $i = 1, \ldots, M$

cd_{up_it} delivery cost of a product up_i at each time step, $i = 1, \ldots, K$

cr_{up_it} removal cost of a product up_i at each time step, $i = 1, \ldots, K$

ms_{up_it} the maximum amount of up_i that can be supplied in a time step, $i = 1, \ldots, K$

mr_{up_it} the maximum amount of up_i that can be removed in a time step, $i = 1, \ldots, K$

c_{up_i} capacity of a storage associated with a product up_i, $i = 1, \ldots, K$

Variables:

Au_{up_ijt} the amount of up_i used by the device d_j, $i = 1, \ldots, K$, $j = 1, \ldots, N$

Ap_{up_ijt} the amount of up_i produced by the device d_j, $i = 1, \ldots, K$, $j = 1, \ldots, N$

As_{up_it} the amount of up_i supplied in a time step, $i = 1, \ldots, K$

Ar_{up_it} the amount of up_i removed in a time step, $i = 1, \ldots, K$

Sp_{s_ijt} number of units of service s_i produced by device d_j, $i = 1, \ldots, M$, $j = 1, \ldots, N$

X_{jt} the intensity at which d_j is to be operated at each time step, $j = 1, \ldots, N$

L_{up_it} currently stored level of a product up_i, $i = 1, \ldots, K$, when $t = 0$, it expresses initial stored amount of product up_i

Product model

In a household (or a community) there are K different products $up_1, \ldots, up_K$ that can be delivered and/or removed by the infrastructure or from naturally available resources. These products are used and processed by N different devices $d_1, \ldots, d_N$ that deliver varying amounts of M services $s_1, \ldots, s_M$ that are essential to satisfying basic human needs. The products that can be used in the solution are limited by L different prohibited products $proh_1, \ldots, proh_L$ ($L \subset K$).

Let ms_{up_it} be the maximum amount of product up_i that can be supplied in a time step and mr_{up_it} be the maximum amount of product up_i that can be removed in a time step for $i = 1, \ldots, K$ and $t = 1, \ldots, T$. The supplied amount of utility product As_{up_it} must be no greater than the maximum amount that can be supplied at each time step ms_{up_it}, i.e.

$$As_{up_it} \leq ms_{up_it}, \tag{3.1}$$

for $i = 1, \ldots, K, t = 1, \ldots, T$

Similarly, the removed amount of utility product Ar_{up_it} for $i = 1, \ldots, K$ must be no greater than the maximum amount that can be removed at each time step mr_{up_it}, i.e.

$$Ar_{up_it} \leq mr_{up_it}, \tag{3.2}$$

for $i = 1, \ldots, K$, $t = 1, \ldots, T$

Device model

Let mt_{d_j} be the maximum throughput if a device d_j and X_{jt} be the intensity at which d_j is to be operated at each time step for $j = 1, \ldots, N$, and

$$mt_{d_j} \geq X_{dt} \geq 0, \tag{3.3}$$

for $j = 1, \ldots, N, t = 1, \ldots, T$. The intensity specifies the capacity at which the device operates.

Let $Au_{up_i jt}$ be the amount of product up_i used by the device d_j in a time step, and $Ap_{up_i t}$ be the amount of up_i produced by the device d_j in a time step for $j = 1, \ldots, N$. Each device has a specific operational principle that defines the relationship between inputs $in_{1j}, in_{2j}, \ldots$ and outputs $out_{1j}, out_{2j}, \ldots$ for $j = 1, \ldots, N$. This relationship as well as the intensity at which device is to be operated determines the amounts of products up_i that will be used and produced by the device d_j as shown in Figure 3.3, i.e.

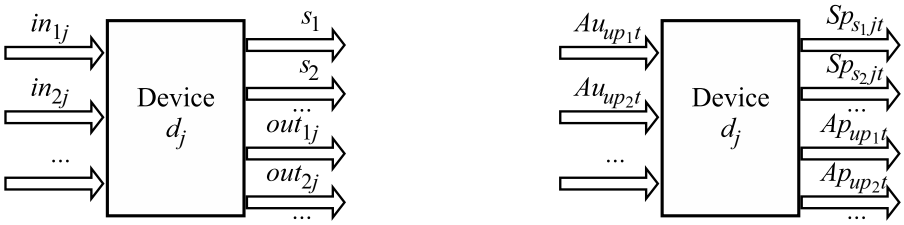


Figure 3.3: Device model

$$Au_{up_i jt} = X_{jt} in_{ij} \tag{3.4}$$

$$Ap_{up_i jt} = X_{jt} out_{ij} \tag{3.5}$$

Service model

Each service $s_1, ..s_M$ has a specified demand $sd_{1t}, \ldots, sd_{Mt}$ at each time step, and

$$\sum_{j=1}^{N} Sp_{s_i jt} x_{jt} \geq sd_{it}, \tag{3.6}$$

for $i = 1, \ldots,\ M, t = 1, \ldots, T$, where $Sp_{s_i jt}$ is the amount of service s_i that can be produced by the device d_j in a time step.

Storage model

Each product used within a solution has associated storage as presented in Figure 3.4. Each of them has a capacity $c_{up_1}, \ldots, c_{up_K}$ as well as currently stored amount of a product $L_{up_1 t}, \ldots, L_{up_K t}$:

$$L_{up_it} = L_{up_i(t-1)} + \sum_{j=1}^{N} \left(Au_{up_ijt} - Ap_{up_ijt}\right) X_{jt} + As_{up_it} - Ar_{up_it}, \tag{3.7}$$

for $i = 1, \ldots, K$, $t = 1, \ldots, T$.

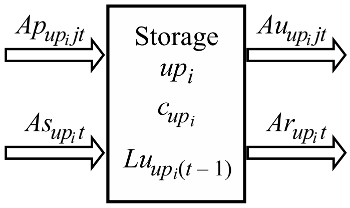


Figure 3.4: Storage model

At each time step currently stored amount of a product must be no greater than storage capacity, i.e.

$$L_{up_it} \leq c_{up_i}, \tag{3.8}$$

for $i = 1, \ldots, K$, $t = 1, \ldots, T$.

Cost model

Each product has associated costs: delivery cost $cd_{up_1t}, \ldots, cd_{up_Kt}$ and removal cost $cr_{up_1t}, \ldots, cr_{up_Kt}$, where $cd_{up_it} \geq 0$ for $i = 1, \ldots, K$ and $t = 1, \ldots, T$ as cost of delivering a utility product must be non-negative. Some products, such as rain, wind, etc. are considered to be free, i.e. $cd_{up_it} = 0$, for $i = 1, \ldots, K$ and $t = 1, \ldots, T$. However, removal cost can have a negative value, e.g. when electricity is sold back to the grid. Therefore, the cr_{up_it} is considered to be unrestricted for $i = 1, \ldots, K$ and $t = 1, \ldots, T$.

The total cost of a candidate solution can be calculated as:

$$\sum_{i=1}^{K} \left(\sum_{t=1}^{T} \left(As_{up_it} cd_{up_it} + Ar_{up_it} cr_{up_it}\right) + \left(L_{up_iT} - L_{up_i0}\right) \sum_{t=1}^{T} \left(\frac{cr_{up_it}}{T} \right) \right) \tag{3.9}$$

The total cost also includes the cost of removal of the difference between the final L_{up_iT} and the initial L_{up_i0} stored amount of a product up_i. As the cost of removal can vary, the average removal cost is used for this calculation. This assumption prohibits from defining storages with very large capacities in order to avoid the removal of the product

3.3 Database

The XML database is implemented within the eXist environment [163]. eXist is an open source database management system entirely built on XML technology, also called a native XML database. Unlike most relational database management systems, eXist uses XQuery, which is a World Wide Web Consortium (W3C) Recommendation, to manipulate its data.

Information about products, services, needs, devices and technologies is stored in the XML database. The connection between each of the components is presented in Figure 3.5. Content of the database can be found in Appendix C.

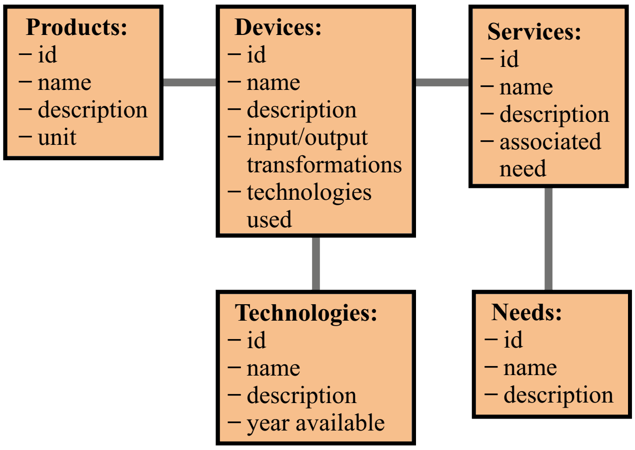


Figure 3.5: Structure of the database

Devices are the most complex component in the database as they use products as inputs and outputs, produce services and use different technologies. Services have associated need that they contribute to satisfying.

The database was initially populated for the purpose of the "All in One" project. The first step to populate the database was to input household appliances in order to understand the inputs requirements that can be delivered either from traditional utility companies, large-scale community projects, household level devices or a combination of them. Later, devices and technologies identified by the researchers in the project as potentially useful for the future utility–service provision approaches were added. These futuristic devices and technologies were obtained from the available literature. For example, Barnatt investigated 25 aspects that will shape the next few decades [37]. He also discussed how technologies and future challenges interrelate, such as nuclear fusion and future transport, or climate change and vertical gardening. Some of the devices and technologies were based on the work conducted by Kaku. He interviewed over 300 scientists around the world in the attempt to find out what will happen in science and technology in the next century [38]. This confirms the approach of many scholars that the dependency of people on technology and software is increasing [39]. The content of the database was also developed to enable numerical analysis of the futuristic visions. Therefore, some of the content of the database is not yet fully developed on a commercial scale, but has a potential to be used in the near future, e.g. 3D food printing, [164].

For the purpose of the "All in One" project software with a graphical user interface (GUI) was developed in C# and .NET 4.0 (Figure 3.6). In the project it included tabs for: devices, utility products, services and technologies. It was expanded by the author to include tabs for needs, problem formulation, transformation graphs and shortest paths. The evolution of the software is described in detail in Section 3.7. The software includes eight tabs: devices, utility products, services, needs, technologies, problem formulation, transformation graphs and shortest paths between elements of the database. This tabs enables adding/removing/editing of products, devices, services, needs and technologies as well as defining and editing of problem formulations and transformation graphs. Detailed explanation of the software is provided in Appendix A.

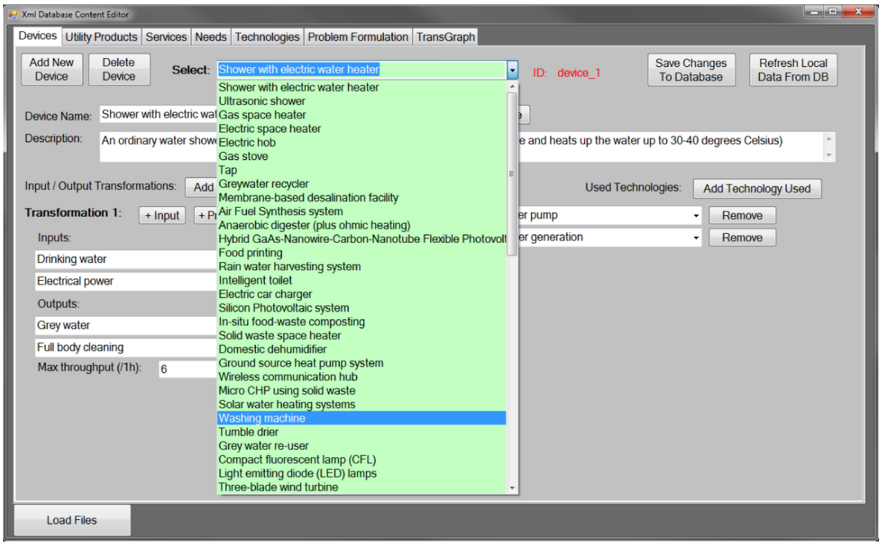


Figure 3.6: GUI for data implementation – device tab

The entire content of the database can be represented in a form of a directed hypergraph, a so-called Mastergraph. In Mastergraph products and services are nodes, while devices are edges spanning between them. Since a device usually connects more than two nodes, the standard graph would not be sufficient to represent utility–service provision problem. This representation and analysis of the Mastergraph is discussed in detail in Chapter 4.

3.3.1 Devices

Devices are the most connected component in the proposed approach to model utility–service provision. The device tab includes:

- Device id,
- Device name,
- Device description,
- Input/Output transformation,
- Used technologies,
- Maximum throughput (per hour). It is related to efficiency of the transformation processes, as it defines how many units of products or services can be produced or satisfied by the device. The ratio between required input and produced output is fixed (i.e. no dynamics).

Devices are divided into two types: (i) *service devices* (Figure 3.7.a) that transform products into services (and sometimes additionally products), and (ii) *conversion devices* (Figure 3.7.b) that transform products into other products, but no services. The *service devices* can usually be found in the households as they are responsible for delivering services that ultimately contribute to satisfying fundamental human needs. On the other hand, the *conversion devices* are most likely to be found outside the household, as they include recycling devices that are usually not placed directly in the living area, but might be found in the basements, on the rooftops, or in general proximity of a house.

The operational rules of the *service devices* depend on the service demand defined in the problem formulation and later updated in the transformation graph. The operational rules of the *conversion devices* are calculated at each step and depend on each of the products and constraints in the problem formulation.

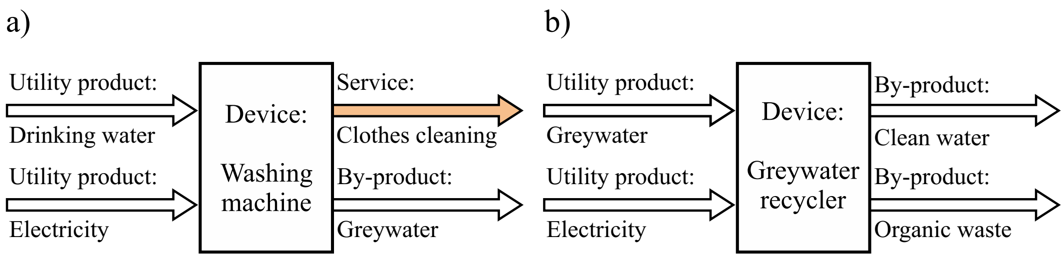


Figure 3.7: An example of: a) a service device, and b) a conversion device

```xml
<device>
  <id>device_5</id> <!-- id must be unique for each device -->
  <name>Electric hob</name>
  <description>Conventional hob used to cook and provide hot food using electricity</description>
       <!-- optional -->
  <input-output-transformations>
    <in-out-transformation> <!-- ALL inputs within one in-out-transformation must be provided to
         produce outputs, ALL outputs are produced -->
      <inputs>
        <product amount-required="3">product_3</product> <!-- product_id -->
        <product amount-required="4">product_6</product> <!-- product_id -->
      </inputs>
      <outputs>
        <product amount-produced="1.5">product_7</product> <!-- product_id -->
        <service amount-produced="1">service_5</service> <!-- service_id -->
      </outputs>
      <maximum-throughput>5</maximum-throughput> <!-- assuming time step 1h -->
    </in-out-transformation>
  </input-output-transformations>
  <technologies-used> <!-- optional -->
  <technology>tech_2</technology> <!-- technology id -->
  </technologies-used>
  <community>yes</community> <!-- Scale specified, if 'yes' the device can only be for community
       scale solutions. Otherwise, it is considered a household scale solution (even if missing)
       -->
</device>
```

Listing 3.1: XML structure – device

Most of devices stored in the database are existing appliances or devices currently emerging/under development. However, some of them are hypothetical devices which may emerge in the future. Therefore, each device uses technologies that are tagged with year of first availability to enable modelling of near future and distant-future approaches to utility–service provision problems [24, 22]. Assignment of technologies to devices is not mandatory, i.e. if no technologies are assigned to a device it will be considered available for any year of simulations.

The structure of a single device in the XML format is presented in Listing 3.1. Devices transform products into other products and/or services. They are also using various technologies, which in turn, limit their availability depending on the year of simulation.

Each device must have an unique id. Additionally, a transformation, defined as the conversion of a product/service into another product/service, must be defined. This transformation should specify the products/service, their quantity used by the device, and the maximum throughput, i.e. how many times device can operate according to the transformation during one time step. The device can by specified as “community scale” only, and will be only available if a “community scale” solution is being tested.

```xml
<utility-product>
  <id>product_10</id>
  <name>Carbon dioxide</name>
  <description>Generally in gaseous form. 1 molar mass of CO2 = 44.56 g/mol. </description>
  <units>kilogrammes</units>
</utility-product>
```

Listing 3.2: XML structure – product

3.3.2 Products

For products the fields in the database are as follows:

- product id,
- product name,
- product description,
- units.

The XML structure of each product is presented in Listing 3.2. Products are used by devices. They are either converted into other products and/or services.

There are several types of products:

- Utility products – products that are provided by utilities, i.e. electricity, water, gas.
- By-products – products that are obtained from conversion devices, i.e. via transformation, these products can be used for further transformations and are not required to be removed from the system (this is determined in the problem formulation).
- Natural resources – products that can be transformed using devices into utility products.
- Waste products – products that cannot be processed and need to be removed from the system.

Products can be produced by different devices. Electricity can be produced from various natural resources and in this approach is considered as the same product, no matter what the conversion was. Additionally, in the candidate solutions (transformation graphs) each product has an associated storage. Therefore, at each time step each product is gathered in its storage. If this product is needed at any particular time, it is supplied by its storage, unless it can be supplied by the infrastructure. Some of the storages are theoretical as their capacity can be assigned as 0. Therefore, the product with such a storage will be directly supplied/removed from/by the infrastructure/natural sources.

Another important assumption of the model is that storages are not considered as devices, i.e. they do not require any products to operate. This is a simplification of reality as in many cases storing products would require additional resources, e.g. hot water tank would require an energy source to keep the water temperature at a certain level.

3.3.3 Services and Needs

Services contribute to satisfying human needs. Each service in the database has associated devices that can deliver this service. Sometimes, the same device can deliver different services, for example a kitchen tap can provide water for drinking as well as water for cleaning and outdoor use. The needs that can be satisfied by provision of products are listed in Table 3.1. They were later divided into secondary needs and into services.

For services there are:

– Service id,
– Service name,
– Service description,
– Associated need.

For needs there are:

– Need id,
– Need name,
– Need description.

The model is focused on delivering services. In order to enable the simulation the service definition were simplified, e.g. there is a specific amount of time (6 minutes) assigned to showering that will satisfy the service of *full body cleaning*. It is not an actual representation of reality, as some people take much longer showers, while others take shorter, but for the purpose of simulation an average value was assigned to this service. Similarly, the the service *provision of drinking water* the assumption is that to satisfy one unit of this service 2 litres of drinking water must be delivered. This might vary for a person to person, but was taken as an average here. Since the majority of energy is used for space heating it is worth mentioning that this service has been also simplified. There is extensive research conducted just in this topic, where various aspects are taken into account, such as the size of the property, the insulation of the building, the behaviour of the occupants, the efficiency of the space heaters, just to name a few. However, in

Table 3.1: Human needs divided into services

Fundamental needs	Secondary needs	Services
Adequate level of comfort	Optimum humidity	Humidification Drying
	Optimum temperature	Thermal comfort - Heating Cooling
	Sufficient amount of fresh air	Ventilation
	Sufficient amount of light	Lighting
Access to information	Visual, Textual, Sound information	Information access
Access to transportation	Car charging	Electric car charger
Adequate level of personal hygiene	Water for bathing and showering	Full body cleaning
	Water for partial body cleaning	Partial body cleaning
Adequate quantity and quality of drinking water	Safe drinking water	Provision of drinking water
Clean environment	Clean interiors	Floor cleaning Window cleaning
	Clean clothes	Clothes cleaning
	Washing dishes	Washing dishes in the sink Washing dishes in the dishwasher
Adequate nutritional food	Cold food	Refrigeration Freezing
	Hot food	Nutrition
Physical activity	Fitness	Home gym
Provision of adequate sanitation	Disposal of solid waste	On-site processing of solid waste Removal of solid waste
	Disposal of liquid waste	Removal of liquid waste On-site processing of liquid waste

the approach presented in this thesis the complexity of this problem has been analysed in terms of the device to deliver this service to be on or off. All services are defined in the database and their definitions can be found in Appendix C.

The XML structure for services is presented in Listing 3.3 while the structure for needs is presented in Listing 3.4. Services are produced by devices and they contribute to satisfying human needs.

There are also services in the database that are not connected to basic human needs, but wants, i.e. charging electrical appliances, water for plant watering and outdoor use or fertigation. With the former representing a combined irrigation and fertilization.

```
<service>
  <id>service_1</id> <!-- id must be unique for each service -->
  <name>Full body cleaning</name>
  <description>A service which cleans body hence contributes to satisfaction of the need personal
      hygiene; can be provided e.g. by a shower device</description> <!-- optional -->
  <devices> <!-- list of all devices which supply this service -->
    <device>device_1</device><!-- device_id -->
    <device>device_8</device><!-- device_id -->
  </devices>
  <!-- Associated need -->
  <need>need_4</need><!-- need_id -->
</service>
```

Listing 3.3: XML structure – service

```
<need>
<id>need_1</id><!-- id must be unique for each need -->
<name>Adequate level of level of comfort</name>
<description> </description><!-- optional -->
<services> <!-- list of all services which contribute to satisfying this need -->
<service>service_2</service> <!-- service id -->
<service>service_9</service> <!-- service id -->
</services>
</need>
```

Listing 3.4: XML structure – need

3.3.4 Technologies

Technologies are the collection of engineering solutions or techniques that are used by devices. Technologies are tagged with the first year of availability to enable simulating past, existing, near-future and distant-future utility–service provision problems. There are 104 technologies stored in the database. The mandatory fields for technologies are:

- Technology id,
- Technology name,
- Technology description,
- First year available.

Technologies limit the availability of devices based on the year of first availability. If no technology is assigned to a device this would result in that device being available no matter what is the year of simulation. Technology *Reverse osmosis membranes* is used by device *Membrane-based desalination facility*. This technology has a year of first availability as 1970. Therefore, if a scenario was tested for a year 1960 the aforementioned device would not be available for building a solution. Moreover, if this device would have been selected while manually constructing the transformation graph, the simulation would not run as it would be considered not feasible, and the system would prompt the user to change the device to one that is available in 1960. The XML structure for technologies is presented in Listing 3.5

```xml
<technology>
  <id>tech_2</id> <!-- id must be unique for each technology -->
  <name>Power generation</name>
  <description>Enables constant generation and supply of electrical power</description> <!--
      optional -->
  <devices> <!-- list of all devices which use this technology, make sure to update this field
      when a new device is added -->
    <device>device_1</device> <!-- device id -->
    <device>device_2</device> <!-- device id -->
  </devices>
  <year-available>1900</year-available> <!-- optional -->
</technology>
```

Listing 3.5: XML structure – technology

3.4 Problem Formulation

Problem formulation determines how the utility–service provision will be solved through a set of requirements and constraints. It defines the type of products, devices, how long services are provided, etc. This formulation requires to define:

- Year for which the utility–service provision problem is considered. It determines the availability of technologies in the database which, in turn, can limit the number of devices that can be used for this specific year.
- Define simulation horizon. The shortest time horizon is 1 hour, which corresponds to a single time step in the simulations.
- Define the service demand as a function of time. This also influences the content of the Mastergraph.
- Specify availability of the products and associated costs of supply/removal as a function of time. The products have several options:
  - Can be supplied/removed by the infrastructure.
  - Cannot be supplied, but can be obtained via transformations.
  - Cannot be removed, therefore must be transformed into another product.
  - Cannot be used at all in the transformation graph, i.e. prohibited product.
- Define maximum capacities for products' storages.

The problem formulation is defined in an XML format an in Listing 3.6:

```xml
<?xml version="1.0" encoding="UTF-8"?>
<scenarios>
  <scenario>
    <id>scenario_1</id>
    <year>2012</year> <!-- year for which scenario is tested -->
    <simulation_horizon>24</simulation_horizon> <!-- number of time steps - single time step is 1
        hour -->
    <services> <!-- list of services to be delivered -->
      <service>
        <service_id>service_1</service_id> <!-- service id corresponding to the XML database -->
        <demand> <!-- defined as number of units of each service per time step. Units of each
             service are defined in the XML database -->
          <time_series> <!-- can be defined per each time step explicitly -->
            <ts step = "8">2</ts>
            <ts step = "20">2</ts>
            <ts step = "9" repeat = "7">1</ts> <!-- or defined by repetition, i.e. starting time
                 step 9 repeat every 7 time steps -->
          </time_series>
          <!-- or -->
          <fixed>1</fixed> <!-- demand can be fixed for the whole simulation horizon (time series
               not used in this case) -->
        </demand>
        <service_name>Full body cleaning</service_name> <!-- name of the service for information
             only as not used in the simulations -->
      </service>
    </services>
    <products> <!-- list of products to be delivered/removed -->
      <product>
        <product_id>product_19</product_id> <!-- product id corresponding to the XML database -->
        <product_name>Rain water</product_name> <!-- name of the product for information only as
             not used in the simulations -->
        <can_supply>1</can_supply> <!-- whether the product can be supplied by the infrastructure.
             1 = yes, 0 = no -->
        <max_supply><time_series> <!-- max number of units that can be supplied in a single time
             step -->
          <ts step = "1">3.30</ts> <!-- Can also be defined by repetition: <ts step = "9" repeat =
               "7">1</ts> -->
        </time_series></max_supply> <!-- or instead of time series: <fixed>'integer'</fixed> for
             the whole simulation horizon -->
        <can_remove>1</can_remove> <!-- whether the product can be removed by the infrastructure. 1
              = yes, 0 = no -->
        <max_remove><time_series>
          <ts step = "1">3.30</ts>
        </time_series></max_remove>
        <supply_cost>2</supply_cost> <!-- cost of supplying 1 unit of the product -->
        <remove_cost>25</remove_cost> <!-- cost of removing 1 unit of the product -->
        <max_capacity>30</max_capacity> <!-- maxiumum capacity of the storage -->
      </product>
    </products>
    <prohibited_products> <!-- list of products that cannot be used in the transformation graph(s)
          -->
      <product_id>product_20</product_id> <!-- Compost -->
    </prohibited_products>
  </scenario>
</scenarios>
```

Listing 3.6: XML structure – Problem formulation

A graphical user interface was developed and incorporated in the XML database content editor (Figure 3.8). It simplifies definition of problems to be solved. It follows the XML structure. Each problem formulation can be stored in the database. Existing ones can be also edited and saved. There is also the option to export a single problem formulation to an XML file, so it can be used by the simulator. Detailed explanation of the functionalities is located in Appendix A.

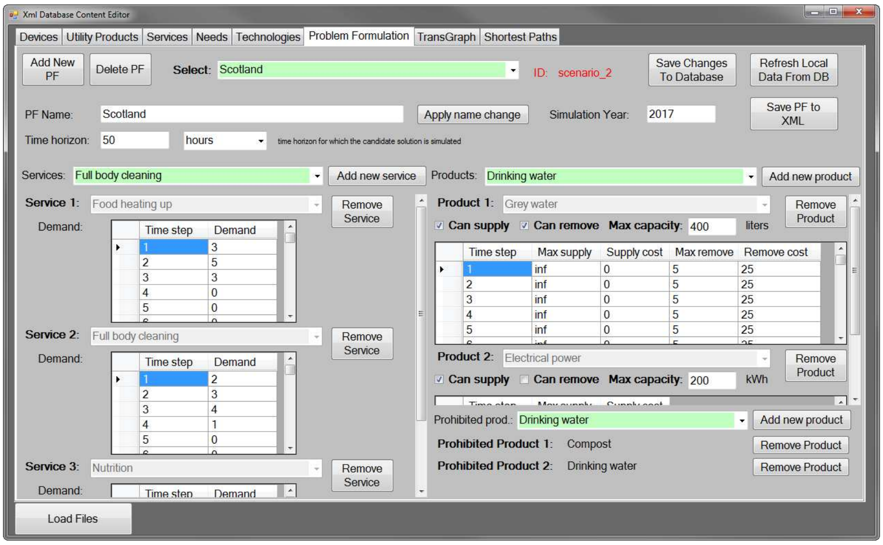


Figure 3.8: GUI for Problem Formulation Definition

3.5 Transformation Graph

A transformation graph is an attempt to represent a solution to utility–service provision problem based on the information about products, devices and services stored in the XML database. Transformation graphs are standard graphs where devices, storages and services are nodes and edges are products or service carriers (Figure 3.9). In the transformation graph the devices are not connected directly to each other. Inputs/outputs are connected to storages for each product. For every product used in the transformation graph, there is only one common storage. Additionally, storages have four thresholds that can be defined [22]:

– remove threshold – push product to removal when stored amount is higher than this threshold;
– push to device threshold – push product to device connected to storage output when stored amount is higher than this threshold;
– pull from device threshold – pull product from device connected to storage input when stored amount is lower than this threshold;

– supply threshold – pull product from supply when stored amount is lower than this threshold.

Devices also deliver services. The services are final nodes and they are not connected to any storages.

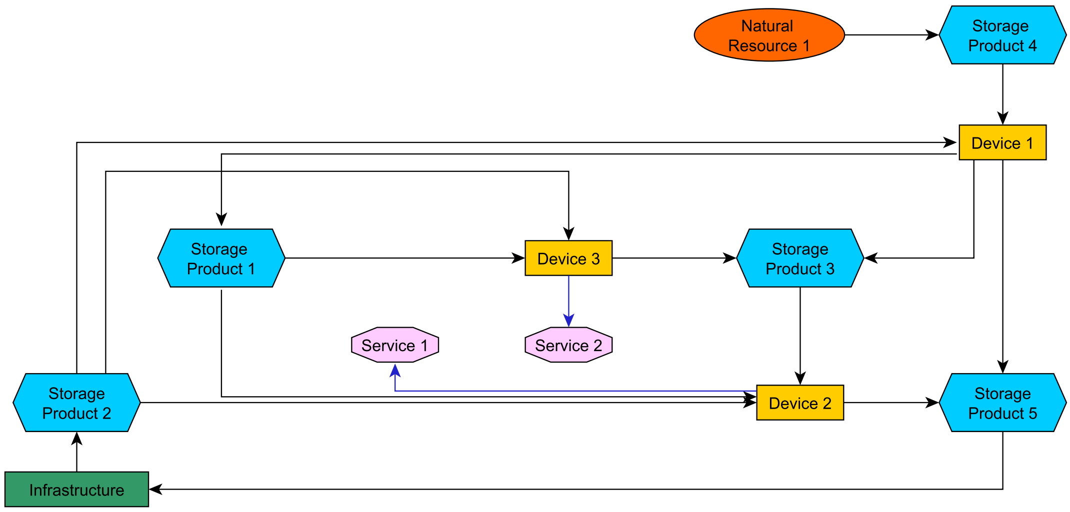


Figure 3.9: Transformation graph structure

The transformation graphs can be created manually (it must follow the structure presented in Listing 3.7) or generated automatically based on the problem formulation. The manual approach is discussed in Section 4.3 as it is based on the Mastergraph. The automatic generation is discussed in Section 4.2.

The graphical user interface was also developed to enable easier definition of the transformation graph (Figure 3.10). For each transformation graph an associated problem formulation must be selected. It is based on the problem formulations stored in the database. Once this is defined the following are sequentially created:

– Service demand – for each service node defined in the problem formulation a table with each time step and associated demand is created. For each service a list of available devices to chose from is created. This list is based on the year for which the transformation graph will be simulated as well as the list of prohibited products. For each service there can be added as many service devices as necessary. When a device is added a new column is created in the original table with the demand. The devices are numbered, and the heading of each column corresponds to that number. Each device can deliver various numbers of units of the service. It must be defined in

```xml
<?xml version="1.0" encoding="UTF-8"?>
<graphml>
<graph id="G1" edgedefault="directed">
  <id>trans_graph_1</id>
  <scenario>scenario_1</scenario><!-- associated problem formulation -->
  <!-- service devices -->
  <node id="n_0"> <!-- each node must have unique node id -->
    <node_type>device</node_type> <!-- allowed node types: device, service, storage -->
    <device_id>device_2</device_id> <!-- device id corresponding to the XML database -->
    <device_name>Device 2</device_name>
  </node>
  <!-- conversion devices -->
  <node id="n_1"> <!-- each node must have unique node id -->
    <node_type>device</node_type> <!-- allowed node types: device, service, storage -->
    <device_id>device_1</device_id> <!-- device id corresponding to the XML database -->
    <device_name>Device 1</device_name>
  </node>
  <!-- storages -->
  <node id="n_2">
    <node_type>storage</node_type> <!-- allowed node types: device, service, storage -->
    <product_id>product_1</product_id> <!-- id of the product that is stored -->
    <remove_threshold>1</remove_threshold> <!-- values between 0 and 1. Values must be higher than
        push to device threshold -->
    <push_to_device_threshold> <!-- values between 0 and 1. Values must be lower than the remove
       threshold and higher than push to pull from device threshold -->
      <dev node_id = "n_1">0.75</dev> <!-- list of devices connected to the storage output -->
    </push_to_device_threshold>
    <pull_from_device_threshold> <!-- values between 0 and 1. Values must be larger than the
       supply threshold. -->
      <dev node_id = "n_0">0.25</dev> <!-- list of devices connected to the storage input -->
    </pull_from_device_threshold>
    <supply_threshold>0.2</supply_threshold> <!-- values between 0 and 1. -->
    <capacity>200</capacity> <!-- Value must be lower than the max capacity defined in the problem
        formulation -->
    <initial_stored_amount>0</initial_stored_amount> <!-- How much of the product is initially
       stored -->
    <name>Product 1</name> <!-- For information only -->
  </node>
  <!-- services -->
  <node id="n_3">
    <node_type>service</node_type> <!-- allowed node types: device, storage, service -->
    <service_id>service_1</service_id>
    <demand>
      <!-- Service demand from the problem formulation can be divided into several nodes, as
         different devices might deliver the overall demand -->
    </demand>
    <service_name>Full body cleaning</name>
  </node>
  <!-- edges -->
  <!-- edges defined between the device and service nodes -->
  <edge source="n_0" target="n_2"/>
  <!-- edges between devices and storages are created autmoatically during the simulation -->
</graph>
</graphml>
```

Listing 3.7: XML structure – Transformation graph the table. The sum of the service outputs of all devices should be equal to the service demand from the problem formulation.

– Storages – the list is created based on the information from the problem formulation. However, once a device is added to the transformation graph its inputs and outputs are checked against this list. If any of the storages for device inputs or outputs is missing, it will be added. Additionally, when a device is added to the transformation graph it will appear in the list of devices connected to the storage input or output, which is related to the thresholds: pull from device and push to device.

– Prohibited products – a list of prohibited products defined in the problem formulation. This list is not editable in the transformation graph tab, it can only be done in the problem formulation tab.

Additionally, there is the option to add conversion devices to the transformation graph. The list of available devices is based on the year for which the transformation graph will be simulated as well as the list of prohibited products. When a device is added their specifications for inputs, outputs and maximum throughput are listed. Additionally, the inputs and outputs are checked against the current storages. If any of the storages does not exist, a node is created. All inputs and outputs of all devices are added to the list of devices connected to the storages inputs or outputs. The detailed explanation of the functionalities of this tab is located in Appendix A.

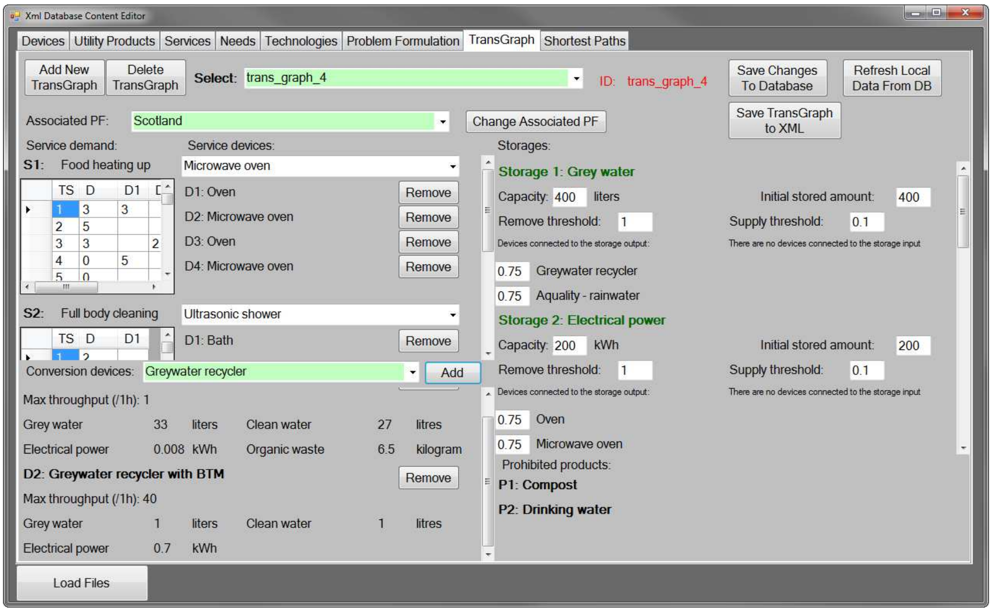


Figure 3.10: GUI for Transformation Graph Definition

3.6 The Simulation System

The simulation system was developed in C# and .NET 4.0. The main functionality of this system is to assess whether a candidate solution (transformation graph) is feasible, i.e. meets all the requirements based on the constraints from the problem formulation. The software consists of 23 classes and 69 methods. It validates the XML input files (problem formulations and transformation graphs), calculates storage levels for all products during the simulation horizon, monitors devices' inputs and outputs, generates output files with results of the simulation as well as GraphML files for visualisation of both transformation graph and Mastergraph. The description of each of the components of the system is in Section 3.6.1 and detailed explanation of the computational engine is in Section 3.6.2.

3.6.1 The main components of the simulation system

The flowchart for the simulation of transformation graphs is presented in Figure 3.11.

The system designed to simulate utility–service provision problems is composed of several blocks as presented in Figure 3.12.

The functionality of each button is:

1. **Load Data** – the content of the XML database is loaded. Information about products, devices, technologies and services are loaded.
2. **Load Problem Formulation** – in format defined in Listing 3.6. The file is processed to check whether it adheres to the structure. An initial transformation graph is created within the simulation system. The following actions take place:

   – Simulation horizon is loaded.

   – Service nodes are created in the internal transformation graph based on the demand specified in the problem formulation. At this point, if there is more than one node for a particular service, or the demand is not specified, the simulation will end and the problem formulation will have to be re-formulated.

   – Prohibited products list is created based on the list in the problem formulation. This limits the availability of devices that can be used in the solution.

   – Storage nodes are created based on the product list and their specifications in the problem formulation. Storages for each product are

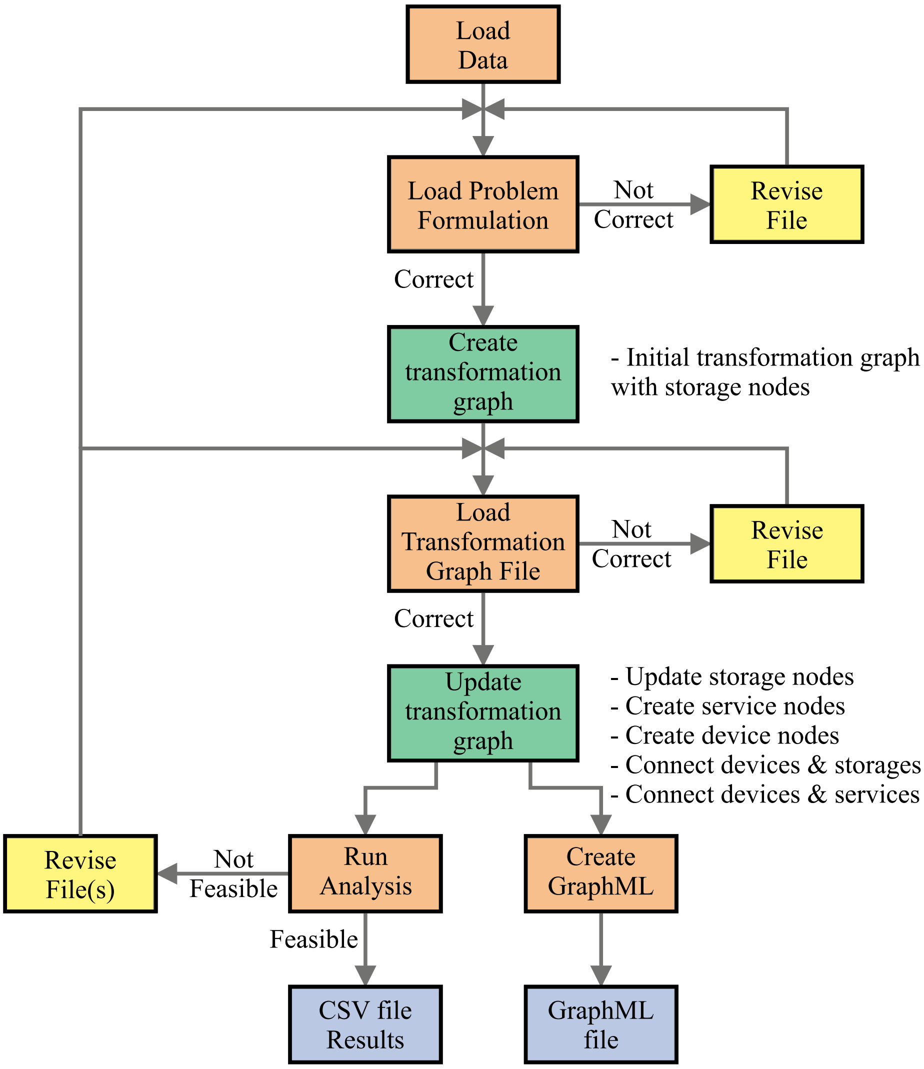


Figure 3.11: Manual approach to simulation of transformation graphs

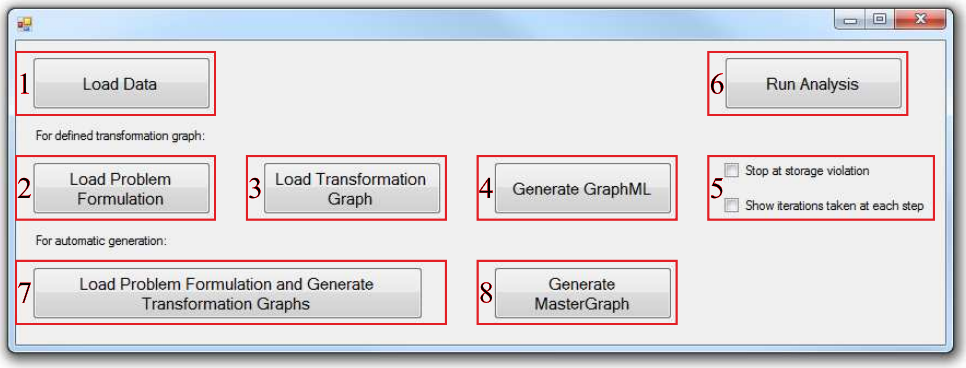


Figure 3.12: Simulation system

tagged with a flag whether they can be supplied and/or removed by the infrastructure. The initial stored amount and the maximum capacity for each storage is defined in the problem formulation. Subsequently, the maximum amounts that can be supplied/removed with associated costs are loaded.

These parameters will be checked with the transformation graph loaded at the next step.

3. **Load Transformation Graph** – manually defined candidate solution according to the structure in Listing 3.7 for the previously loaded problem formulation that will be analysed. The file is also checked to ensure its compliance with the defined structure. In the next step the initial transformation graph that was created while loading the problem formulation is updated with the information from this file. The following parameters are updated:

   – create storage nodes based on the XML file. First it is checked if each storage node has already been created when problem formulation file was loaded. If any of them was not created then, a new storage node is created and the product is tagged as one that cannot be supplied nor removed by the infrastructure (if that is supposed to be the case, it should have been declared in the problem formulation file). Also, all devices are connected to the appropriate storages' inputs and outputs which is related to the thresholds: pull from device and push to device.

   – create service nodes based on the XML file. If, in the transformation graph, the service node from the problem formulation was divided into several nodes, the overall demand that can be satisfied by chosen devices is compared with the overall demand from the problem formulation file.

   – upload edges between device and service nodes based on the XML file.

4. **Generate GraphML** – based on the transformation graph created using the problem formulation and the transformation graph from the previous steps a GraphML file is generated and can be used for visualisation in yEd software [165]. Additionally, an XLS file containing an incidence matrix and two modified matrices with inputs and outputs is created. Explanation of the matrices can be found in Section 4.3.1.

5. **Stop at storage violation** and **Show iterations taken at each step** – the simulation ends if the storage capacity has been exceeded (if the check-box is checked). However, for the purposes of simulations it is sometimes useful to run the analysis with some of the storages being violated. This information can be used to re-define the initial conditions defined in the

problem formulation. This information is available in the output CSV file once the simulation is run.

6. **Run Analysis** – the transformation graph created in the previous steps is analysed and simulated. Described in Section 3.6.2.
7. **Load Problem Formulation and Generate Transformation Graphs** – Based on the problem formulation a set of feasible transformation graphs is generated. They are analysed and CSV files with results are generated as well as GraphML files for each transformation graph for visualisation. The methods used for this step are described in detail in Chapter 4.
8. **Generate MasterGraph** – a GraphML file is generated that allows visual representation of the entire content of the database in a form of a hypergraph. The file can be visualised using yEd software.

3.6.2 Feasibility Analysis

The aim of the simulation system is to assess the feasibility of the proposed/generated transformation graph(s). Therefore, the system calculates whether it is possible to satisfy the service demand specified in the problem formulation taking into consideration the constraints on resources and technologies availabilities. With this in mind, there are two types of devices in the system, each having different operational rules. On the one hand there are service devices that are only operating when there is a demand for the service they are producing. On the other hand there are conversion devices that operate based on the push to device and pull from device thresholds. These thresholds, together with the remaining two: pull from supply and push to removal threshold determine how the conversion devices operate during the simulation horizon.

The algorithm progresses in the following steps:

- Check demand allocation – check if all demands defined in problem formulation file are allocated suitable demand nodes in the transformation graph.
- Check storage capacities – check if allocated capacity (defined in the transformation graph XML file) is smaller or equal to the allowed maximum capacity (defined in problem formulation).
- Check prohibited products – check if any product from the prohibited list (defined in problem formulation) is used in the transformation graph.
- Connect all unconnected devices and storages – when defining the transformation graph only the connections between device nodes and service nodes are be made. At this step all device nodes are connected to the appropriate storage nodes.

- Simulate entire transformation graph – at each time step service devices are activated depending on the service demand. Conversion devices are activated based on the storages' thresholds. For all storage nodes that are affected (i.e. they supply and/or they collect products used by devices) balances of products that are coming in and out are calculated at each time step. Depending on the checkbox "stop at storage violation" marked as 5 in Figure 3.12 the simulation will end if the stored product level exceeds maximum or drops below 0 - if the box is checked. However, if the box is unchecked, the simulation will continue. This is useful, as sometimes storages are too small, but the transformation graph is otherwise correct. During the simulation the cost of supplying and removing each product is calculated. Additionally, initial and final stored amounts of the products are taken into consideration to calculate total cost of the solution.
- CSV file is generated. It contains: inputs and outputs of each device at each time step, the storage levels at each time step, total cost of the solution.

3.7 Evolution of the approach post the "All in One" project

Research presented in this thesis is based on the model developed in the "All in One" project. During the project different De Montfort University team members were responsible for the following aspects:

- the initial structure of the XML database as well as the graphical interface for data manipulation was developed in the "All in One" project. The structure was later updated by the author of this thesis with additional fields for needs, problem formulation, transformation graph and shortest paths.
- the structure of the XML files for transformation graphs and problem formulations was developed by the author of this thesis.
- during the project the database was populated by the researchers from De Montfort University.
- the simulation approach was developed jointly with the supervisory team, initially implemented jointly and later taken over by the author of this thesis.
- the approach to represent the entire content of the database in a form of a hypergraph was developed by the author of this thesis.
- the automatic generation of feasible transformation graphs was developed and implemented by the author of this thesis.

The research was later conducted by the author of the thesis with the support of the supervisors. The major changes in the adapted modelling approach compared to the one when the "All in One" project ended are summarized in Table 3.2. The main contribution is the introduction of the automatic generation of feasible transformation graphs.

Table 3.2: Evolution of the approach post the "All in One" project

	At the end of "All in One" project	Current status
XML database content	63 devices 95 technologies 39 products 23 services No needs included	96 devices 95 technologies 39 products 23 services 17 needs
Problem formulation	Year of simulation Simulation horizon Service demand Product specification	Prohibited products added Interface for definition added
Transformation graph	Directed graph Devices connected to storage nodes or to service nodes Defined in XML file	Interface for definition added
Simulator	Simulate one transformation graph Mass balances & total cost calculation	Automatic generation of transformation graphs added
Automatic generation	Single transformation graph No feedback loops No optimisation	All feasible transformation graphs Products' recycling included Heuristic approach included to minimise the cost of solutions
Mastergraph	Exported to GraphML	Graph analysis added Shortest hyperpaths calculation

Chapter 4

Heuristic search approaches

4.1 Introduction

The main aim of the optimisation process is to find the best possible solution to the considered problem. However, in order to assess whether a solution is the "best possible" criteria for assessment must be made, i.e. some predefined measures bounded by a set of constraints [166]. In the case of utility–service provision these criteria depend on the user and his/her objectives. The main objective is to reduce the cost of the solution. However, this might also include constraints on the amount of products delivered and/or removed from a household, or the number of devices used for recycling, maximise use of locally available resources.

In order to optimise any model/process an appropriate technique must be selected. Since the utility–service provision problem can be described as a directed hypergraph, the natural choice would be to use graph methods. The directed hypergraph, which represents complete content of the database, is called Mastergraph [19]. The paths on Mastergraph from product A to service B show which transformations are required to satisfy B by supplying A. They also show which transformations are required to transform product A into product C [24]. In Section 4.3 the adopted approach is presented. It was decided to use the graph theory to analyse Mastergraph in order to build transformation graphs. This analysis includes its statistical properties such as degree distribution, path lengths, cardinality of nodes, etc.

The main concern of the adopted approach was to enable automatic generation of feasible transformation graphs. The graph theory was initially employed for this task, mainly finding shortest paths. This approach is used in countless practical applications [167, 168, 169]. There are several approaches towards finding the shortest path in a graph. One of the possibilities includes searching for the shortest path between one node and the other one, i.e. checking whether it is possible to deliver desired service by provision of one utility product. Another possibility is to search for the shortest paths between one node and all others. It can be useful in checking if there is a possibility to deliver all desired service by provision of one utility product, e.g. delivering a utility product drinking water and to see which services can be delivered by provision of this particular product. However, this can work in the other way around as well (connection between services and utility products). The next possibility included searching for a shortest path between two or more nodes that will include specific nodes in between, i.e. a path between one utility product node and a service node that will include a specific device. The search of the Mastergraph results in finding (or not) a path between those two nodes as well as the desired device. However, in the case of utility–service provision these approaches proved to be unsuccessful as the shortest path is often the best solution to transform one product into another product. As the main aim is to introduce alternative approaches towards current utility–service provision approach, devices for recycling should be included. They often are not located on the shortest path from one node to the other. An algorithm to search for shortest hyperpaths in Mastergraph was developed and implemented and its usefulness discussed, see Section 4.3.2.

In order to automatically generate transformation graphs a heuristic search approach was adopted. Heuristic models employ intuitive rules and provide good solutions [160]. They are usually divided into four categories: limitation of the search area, decomposition of the search problems, limitation of the links searched, and a combination of the previous three [168, 170]. The heuristic methods provide flexibility and allow incorporation of additional rules, e.g. finding a device that uses a product already selected for this particular solution, rather that selecting one that is on the shortest path. Additionally, they prove to be fast and provide near optimal solutions [171]. The adopted heuristic model is explained in Section 4.2. It can be summarized as follows: based on the problem formulation an initial transformation graph consisting only of service demand nodes is automatically constructed. Subsequently, an iterative algorithm searches the knowledge base for suitable devices, inserts them into the transformation graph, simulates the graph and analyses the results to decide what needs to be done (e.g. what kind of device needs to be inserted) during the next iteration. In the selected heuristic approach, such suitable devices are those that: (i) satisfy the specified service demands, (ii) acquire useful utility products from locally available natural resources, (iii) recycle by-products of devices already in the graph to produce useful utility products. If during a particular iteration more than one device satisfies some criterion (e.g. a device that produces service A needs to be inserted and two such devices exist in the knowledge base), then the current transformation graph is copied and the algorithm proceeds with both copies independently. Consequently, the final output of the algorithm is a collection of transformation graphs that satisfy the specified requirements and constraints.

4.2 Heuristic search approach

4.2.1 Most widely known heuristic techniques

Heuristic search approaches are often used when application of formal optimisation methods is not practical, e.g. due to large computational times. The heuristics often provide acceptable quality solutions in shorter computational times [160, 172]. They find feasible solutions that are close to optimal solutions. They are used in many fields, such as constraints satisfaction problems [173], production scheduling [174], Artificial Intelligence [175] or automated planning [176]. There are different types of heuristic search algorithms:

- Exhaustive search – based on a predetermined set, the algorithm tries all possible solutions, and selects the best one [177];
- Local search – it is one of the greediest heuristics, as it only accepts a new solution when it is better than the best solution found so far [160];
- Divide and conquer algorithms – it divides the problem into sub-problems and solves these sub-problems. The limitation of this approach is the fact that not many problems can be decomposed in such a way [177];
- Branch and bound approach – is a well know partitioning algorithm that tries to eliminate the parts of the search space that do not contain the best solution [178];

There are many heuristics algorithms that can be adopted to solve various problems [160, 172]:

- Hill Climbing – it is a local search algorithm that will not accept a solution unless it is the best solution encountered so far. The algorithm will most likely find a local optimum. It can be sensitive to the starting point of the search.
- Simulated annealing – it is based on the physical process of annealing - its behaviour depends on a parameter ‘temperature’. It enables the escape of local optima, by sometimes accepting lower quality solutions. When

the temperature is high, the algorithm will behave as a random search algorithm. When the temperature is low, the algorithms behaves as hill climbing. The probability of accepting lower quality of solutions decreases with time.

– Tabu search – it is an iterative search procedure that moves from one potential solution to another one. It uses a tabu list that records forbidden movements - reverse moves are not in this algorithms to avoid cycling. The list is updated in every iteration. The list's size affects the performance of the algorithm.
– Genetic Algorithms – they belong to a field of evolutionary algorithms and they start with randomly generated set of solutions (population) and move from one to the other. They allow crossovers and mutations to generate new solutions and evaluate which solution is better.
– Swarm intelligence – the most widely known type is Ant Colony Optimisation where artificial ants move on paths and leave pheromones. The ants that follow choose paths with higher pheromone count, i.e. the shortest paths.

4.2.2 Automatic Generation of Transformation Graphs

A transformation graph is a candidate solution to a specific problem. It is a set of devices that use and produce various products. Manual definition of such transformation graphs is explained in Section 3.5. However, since the aim of the simulation system is to consider alternative approaches to the current utility–service provision, it is worth exploring other possibilities. They can include use of naturally available resources, introducing devices for recycling, or using alternative devices. Therefore, based on the knowledge base, an automated process of generating alternative solutions is proposed. This approach uses heuristic searches of the content of the database and decides which device is best to be included in the possible transformation graph. If, at any point, there is more than one option, a copy of the current transformation graph is created and the system proceeds with both copies. The algorithm finishes once all services are delivered and all products that cannot be removed from the system are converted into other products. The developed heuristic generation of transformation graphs is a combination of the divide and conquer approach as well as the exhaustive search. The combination of these two methods allows to generate all possible candidate solutions and check whether they are feasible.

Based on a defined problem formulation, the algorithm progresses in several steps (see Figures 4.1-4.4):

1. Create an initial transformation graph with service and storage nodes. Based on the Problem Formulation create:

   – *remove false list* – a list of products that cannot be removed by the infrastructure,
   – *supply false list* – a list of products that cannot be supplied by the infrastructure,
   – *supply true list* – a list of products that can be supplied by the infrastructure,
   – available conversion devices list – a list of all available conversion devices under the specified set of constraints,
   – available service devices list – a list of all available service devices under the specified set of constraints,
   – unconnected service nodes list – at the beginning all service nodes are unconnected.

2. Select service devices (Figure 4.1). For each service node in the unconnected service nodes list:

   – Create a list of devices that deliver this service. If there are no devices to deliver this service, the transformation graph is not feasible and the algorithm will end. If there is only one device in the list, this device will be used to deliver this service. If there are n devices in the list n copies of the transformation graph will be created. For each of them the following steps are taken.
   – Add storage nodes for inputs and outputs (if they are not existing already). Each of the new added products cannot be supplied nor removed by the infrastructure.
   – Check whether the device can deliver required number of services. If not, create a new service node. Demand at each time step of this new node will be equal to the difference between the original node and the maximum amount that can be produced by the associated device (or 0 in case the maximum that can be produced by the device is larger than the demand). This new service node will be added to the unconnected service nodes list, while the original one will be removed from the list.

3. Select conversion devices (Figures 4.2-4.4). This procedure applies to all transformation graphs created in the previous step.

   – Create product storages lists: supply true, supply false, remove false. These lists are based on the problem formulation. When new storage

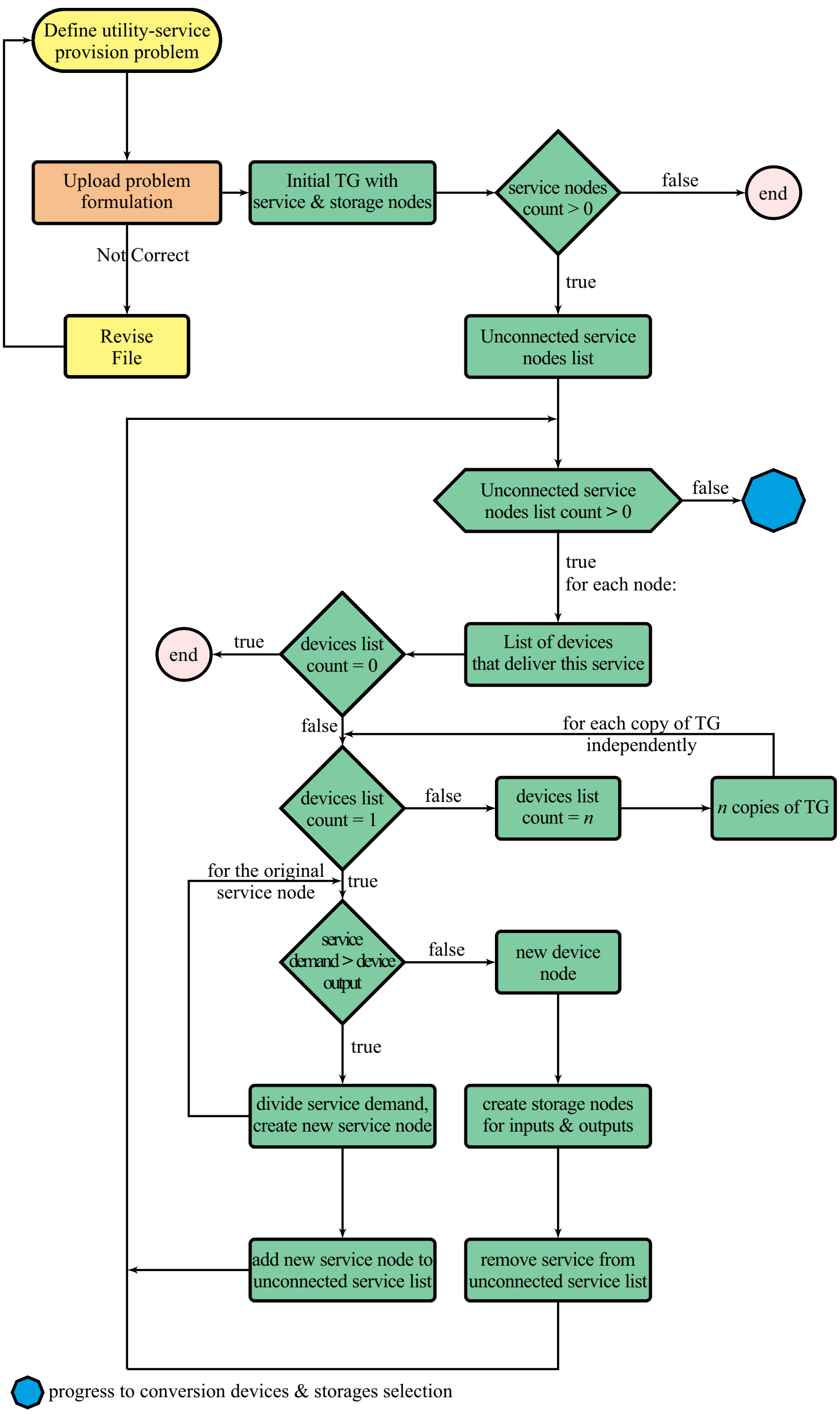


Figure 4.1: Automatic generation - service devices

nodes are added later they are assigned to the supply false and remove false lists.

– For each storage node in supply true list (Figure 4.2): check if there is a device in the transformation graph that uses it as an input. If not, find a device in the available conversion devices list. If any of the conditions is satisfied, the algorithm creates n copies of the transformation graph - based on n number of devices that can process this product. For each copy, maximum throughput of the device is compared with the maximum amount of the product that can be supplied by the infrastructure. If the device cannot process it, additional device of the same type is added to the transformation graph.

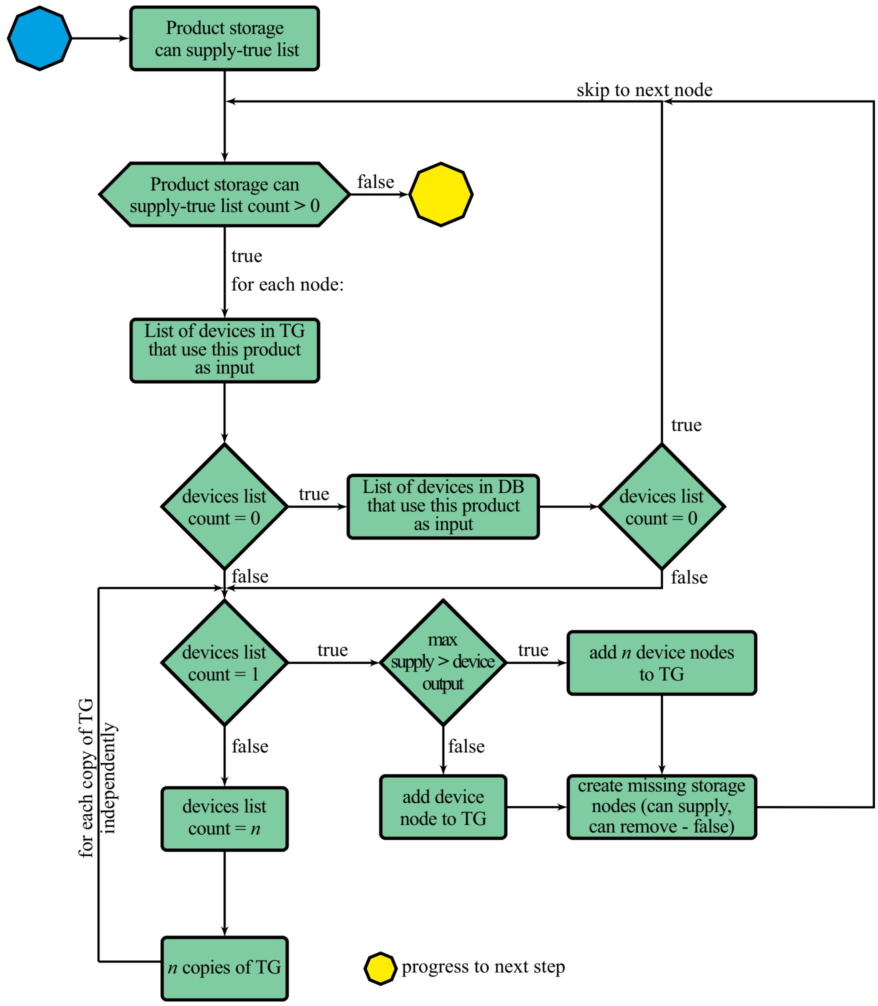


Figure 4.2: Automatic generation - conversion devices for supply-true list

- For the new device added, input and output products are checked against storages existing in the transformation graph. If any one of them is missing, new storages are created.
- For each storage node in remove false list (Figure 4.3) - a similar procedure is adopted. First the transformation graph is traversed to find a device that uses this product as an output. If there is such device, the product will be converted into other products - therefore, the requirements from problem formulation will be met. If this step fails, the list of available conversion devices is checked. If there is no device to convert the product, the algorithm will discard this graph

and progress with another graph.

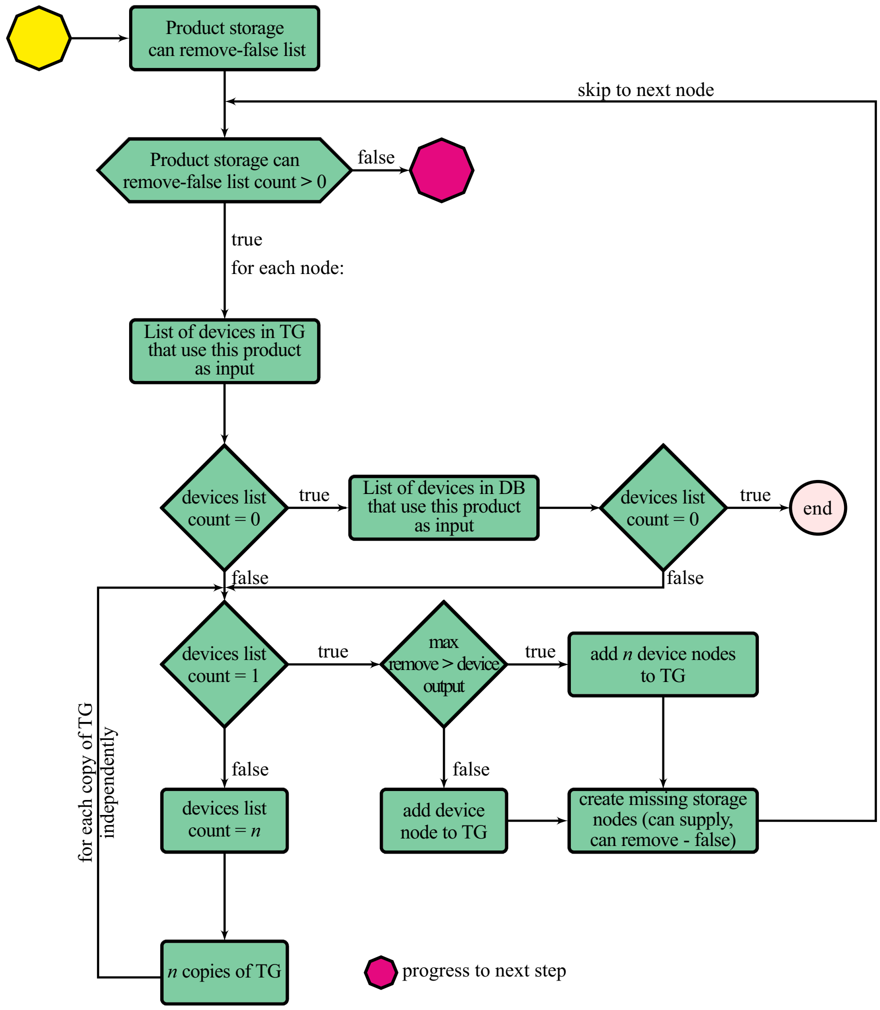


Figure 4.3: Automatic generation - conversion devices for remove-false list

– For each storage node in supply false list (Figure 4.4) - the transformation graph is traversed to find a device that produces this product. If there is no such device, the available conversion device list is checked. If there are no devices that meet this requirement, the current copy of the transformation graph is deleted. If there are n devices that can produce this product, n copies of the transformation graph will be created. For each copy, a device will be selected and its input and outputs checked against the existing storages. If any of them are not existing, they will be added to the graph.

– the algorithm concludes with a set of transformation graphs that meet the requirements from the problem formulation. Each of the graphs is simulated and result files are generated: a CSV file with all mass balances and the total cost of the solution, GraphML file for visualisation in yEd, and XML file with the transformation graph.

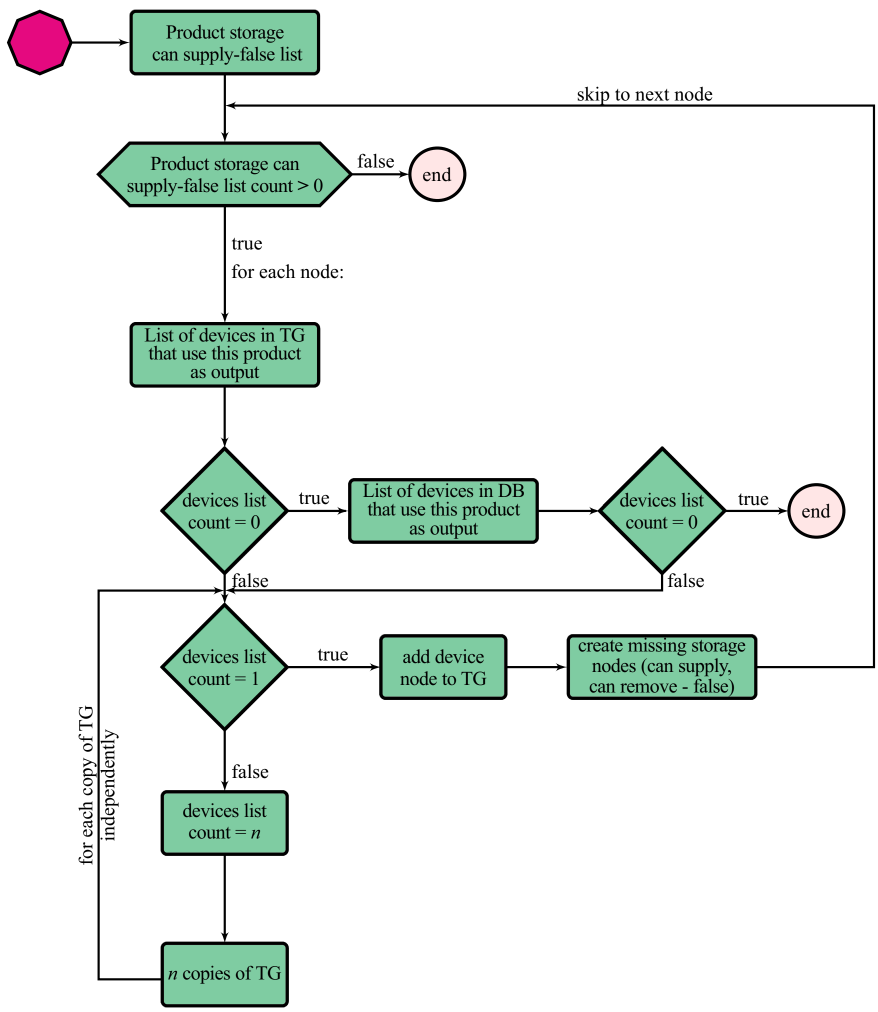


Figure 4.4: Automatic generation - conversion devices for supply-false list

4.3 Graph theory

The analysis of the topology of utility–service provision systems was carried out with two aims in mind: (a) to explore the possibility of delivering all services to households or small local communities via a single utility product by developing visions of future infrastructure [21, 157] and (b) to gain knowledge about the topology of the system prior to building a dynamic simulation model of utility-service provision for the purpose of generating optimum scenarios for utility-service provision under local conditions and with constraints on the type and size of available devices, and the type and quantity of utility products as well as locally sourced products [22].

The content of the XML database can be described in the form of a directed hypergraph in which the products and services are represented by nodes whilst the devices are hyperedges spanning between them. In the case of utility–service provision the use of a standard graph to represent a complex network restricts the user from providing a complete description of the system under investigation, [179] because it shows that one product can be transformed into another products or services, but it does not show which other products are required for that transformation. Typically a device has many inputs and outputs, hence it connects more than two nodes. Hence, a directed hypergraph was selected as the best approach to describe the utility–service provision network with all its products, services, and devices are referred to as a Mastergraph.

4.3.1 Basic definitions

The utility–service provision systems require directed hypergraphs for their description, as the edges (devices) are usually connecting more than two nodes (products or services). Therefore some definitions are introduced. Due to the rather significant size of the mastergraph some of the terms are explained using a simplified utility–service provision problem presented in Figure 4.5. This example can be found in [19]. Basic concepts from set theory that are used in this section are summarized in Appendix B.

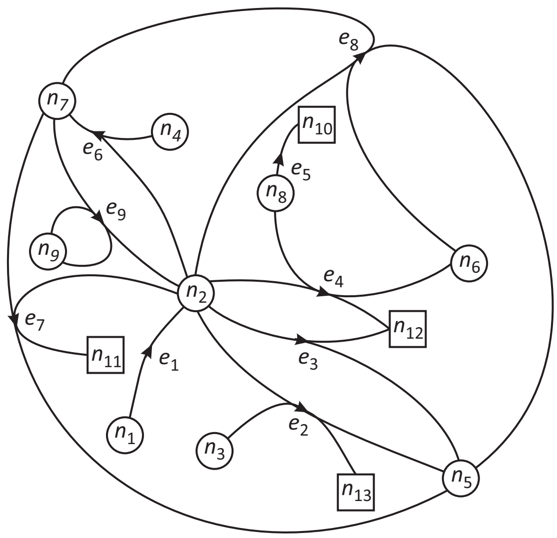


Figure 4.5: A directed hypergraph representing a simplified utility–service provision problem

A *hypergraph* is a pair $H = (N, E)$, where $N = \{n_1, n_2, ..., n_n\}$ is the set of nodes and $E = \{e_1, e_2, ..., e_m\}$ is the set of *hyperedges*. A *directed hyperedge* $e_i \in E$ is a pair $e_i = (T(e_i), h(e_i))$ for $i = 1, ..., m$, where $T(e_i) \subset N$ denotes the set of *tail* nodes and $h(e_i) \in N \setminus T(e)$ denotes the *head* nodes. When $|e_i| = 2$, for $i = 1, ..., m$, the hypergraph is a standard graph [167]. A *directed hypergraph* is a hypergraph with directed hyperedges. In utility–service provision case nodes represent products' storages and services, while edges represent devices.

The example presented in Figure 4.5 consists of 13 nodes and 9 edges. There are two types of nodes in the graph: product storages (represented by circles) and services (represented by rectangles). In this simplified example the selected products are:

n_1 – Solar irradiation,
n_2 – Electricity,
n_3 – Food,
n_4 – Rainwater,
n_5 – Organic waste,
n_6 – Greywater,
n_7 – Clean water,
n_8 – Drinking water,
n_9 – Seawater,

while services are:

n_{10} – Provision of drinking water,
n_{11} – Clothes cleaning,
n_{12} – Full body cleaning,
n_{13} – Nutrition.

In the adopted approach the product nodes are perceived as storages. The role of storage is to accumulate a given product under conditions where product supply or production exceeds demand and to supply the product when demand exceeds the supply. Each edge represents a different device which transforms one or more products into other product or products, or into a service:

e_1 – Silicon Photovoltaic system,
e_2 – Electric hob,
e_3 – Ultrasonic shower,
e_4 – Shower with electric water heater,
e_5 – Tap,
e_6 – Rainwater harvesting system,
e_7 – Washing machine,
e_8 – Greywater recycler,
e_9 – Ocean salinity power generation (reversed electro dialysis).

This particular hypergraph is not acyclic which means that some devices use the same product as an input and output. In this example product n_9 is used as an input and as an output by device e_9.

A standard graph can be defined with a $n \times n$ *adjacency matrix* $[a_{ij}]$ where [180, 181]:

$$a_{ij} = \begin{cases} 1 & \text{if there is an edge connecting node } i \text{ to node } j, \\ 0 & \text{otherwise.} \end{cases} \tag{4.1}$$

However, an adjacency matrix does not provide a representation for directed hypergraphs. They can be defined with a $n \times m$ *incidence matrix* $[c_{ij}]$:

$$c_{ij} = \begin{cases} -1 & \text{if } n_i \in T(e_j), \\ 1 & \text{if } n_i \in h(e_j), \\ 0 & \text{otherwise.} \end{cases} \tag{4.2}$$

This representation is correct for acyclic graphs. However, in the case of the Mastergraph a modification has been made, as the hypergraph is not acyclic, some devices use the same product as an input and as an output. Therefore, the following definition is proposed:

$$c_{ij} = \begin{cases} 2 & \text{if } n_i \in T(e_j) \wedge n_i \in h(e_j), \\ 1 & \text{if } n_i \in h(e_j), \\ -1 & \text{if } n_i \in T(e_j), \\ 0 & \text{otherwise.} \end{cases} \tag{4.3}$$

The incidence matrix (illustrated in Table 4.1) describes the topological structure of the hypergraph. Additionally, colour-code is introduced to make the modified incidence matrix more readable. The storage's product outputs, i.e. *tail* nodes are shown in green and correspond to the value -1 representing an input to the device. Storage product inputs, i.e. *head* node are shown in pink and correspond to the value of 1 denoting the source, i.e. output from the device (service nodes are shown in blue to distinguish them from products). Grey-coded fields represent products that are used both as an input and as an output and correspond to the value of 2. 0 are not included in the representation to make the table more readable. For the example presented in Figure 4.5 the modified incidence matrix is presented in Table 4.1.

The modified incidence matrix shows that product n_2 can only be produced by devices e_1 and e_9 (see row 2) and that product n_6 can be recycled by device e_8, as e_8 is the input to n_6. Therefore, these devices can be used to formulate the candidate solution, i.e. the transformation graph to comply with the constraints

Table 4.1: Incidence matrix for the hypergraph introduced in Figure 4.5; *tail* nodes are shown in green, *head* node are shown in red for devices and blue for services, grey-coded fields represent products that are used both as an input and as an output.

	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9
n_1	-1								
n_2	1	-1	-1	-1		-1	-1	-1	1
n_3		-1							
n_4						-1			
n_5		1	1					1	
n_6				1			1	-1	
n_7						1	-1	1	-1
n_8				-1	-1				
n_9									2
n_{10}					1				
n_{11}							1		
n_{12}			1	1					
n_{13}		1							

listed in a problem formulation. Additionally, Table 4.1 indicates that service n_{10} can be delivered only by device e_5, service n_{11} can be delivered solely by device e_7; service n_{12} can be delivered either by device e_3 or e_4 whilst service n_{13} can be provided by device e_2.

In addition to the modified incidence matrix, which provides information about the topology of the hypergraph, it is beneficial to introduce two more matrices that provide quantitative information about the operating rules of the devices, i.e. how much of a product is used and produced by a given device. The benefit of such representations is that it enables a quantitative comparison of the amounts of products produced or used by corresponding devices and of the amounts of services they generated by these devices. Whilst Table 4.2 presents the maximum amounts of products (inputs) used by all devices in a single time step, Table 4.3 shows the maximum amounts of products and services produced by these devices in a single time step. Since services cannot be used by devices as inputs they are not included in Table 4.2. In both matrices an additional column was introduced. This column shows units for each product.

Each node n_i in a hypergraph has a number of incident edges k_i. The value of k_i defines the *node's degree*, also called its *connectivity* [179]. The higher the node's degree, the more important the node is in the system. However, sometimes the importance of nodes with the same degree is not the same. Furthermore, a node that is connecting such two nodes (a *bridge node*) plays a very important role even though its degree is lower [182]. Additionally, hypergraphs have another property called *cardinality* which defines the number of nodes contained

Table 4.2: Inputs for devices (per time step) used in the example presented in Figure 4.5

	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	Unit
n_1	-0.91									kWh/m^2
n_2		-3	-50	-2		-0.9	-1.2	-0.008		kWh
n_3		-4								kg
n_4						-100				litres
n_5										kg
n_6								-33		litres
n_7							-69		-0.2	litres
n_8				-60	-2					litres
n_9									-0.2	litres

Table 4.3: Outputs for devices (per time step) used in the example presented in Figure 4.5

	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	Unit
n_1										kWh/m^2
n_2	0.1								1	kWh
n_3										kg
n_4										litres
n_5		1.5	0.5					6.5		kg
n_6				60			69			litres
n_7						100		27		litres
n_8										litres
n_9									0.4	litres
n_{10}					1					
n_{11}							1			
n_{12}			1	1						
n_{13}		1								

by a hyperedge. In case of the Mastergraph representing the utility–service provision problem, cardinality shows which products and services a device uses or produces, respectively. The size of a hypergraph H is defined as the sum of the cardinalities of all its hyperedges, i.e.

$$size(H) = \sum_{e_i \in E} |e_i| \tag{4.4}$$

In the example presented in Figure 4.5 the cardinalities of hyperedges are respectively: $e_1 = 2$, $e_2 = 4$, $e_3 = 3$, $e_4 = 4$, $e_5 = 2$, $e_6 = 3$, $e_7 = 4$, $e_8 = 4$, $e_9 = 4$

This parameter shows how many inputs and outputs are associated with each device. Information about cardinality of hyperedges can be useful at the stage of choosing devices for the transformation graphs. The size of the hypergraph is calculated as a sum of all its hyperedge cardinalities. Since the size of this hypergraph is 30 and it contains 9 nodes, a device has on average 3.33 inputs and outputs.

Sensitivity of a hypergraph to critical nodes can be described by *degree distribution* which provides the information on how many nodes in a hypergraph are highly and lowly connected. The more connections a node has the more important it is in the graph as more paths traverse through it. Therefore such a node may be critical to the proper functioning of a system described with such a graph.

Figure 4.6 shows that the degree distribution for the simplified hypergraph follows a power-law function $P(k) \sim k^{-0.9335}$. There are six nodes that have only one connection whilst one node representing electricity has eight connections. This indicates that electricity is crucial for the proper functioning of many, six to be precise (since two connections are electricity inputs not outputs), devices. Information included in the degree distribution of a hypergraph is very important in the analysis of the robustness of the solution as it helps in identifying the nodes that are critical for the operation of the solution system. Overall, the example presented in Figure 4.5 contains nine devices: two are producing electricity and six are requiring electricity to work, while one is independent, i.e. it does not require electricity.

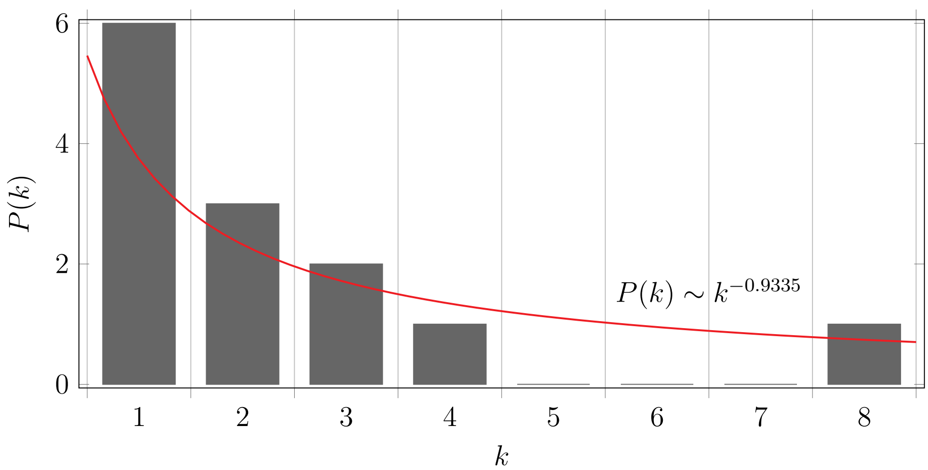


Figure 4.6: Degree distribution in the example

Connections between node n_i and node n_j in a hypergraph are described with hyperpaths, each hyperpath having an associated length. A hyperpath in a hypergraph G is defined as a sequence of hyperedges $\{e_1, e_2, ..., e_m\}$ such that $n_i \in e_1$, $n_j \in e_m$ and $e_i \cap e_{i+1} \neq \emptyset$ for $i = 1, ..., m-1$ [183].

The concept of *shortest hyperpaths* lengths in Mastergraph represent the minimum number of devices that must be used in order to convert product represented by node n_i to node n_j that represents either another product or a service. The *shortest hyperpaths* lengths of a hypergraph presented in Figure 4.5 can be represented as a matrix D in which d_{ij} is the length of the shortest hyperpath from node n_i to node n_j. In order to calculate the shortest hyperpaths in Mastergraph a search algorithm was developed with an interface to calculate them. More details are in Section 4.3.2.

Table 4.4: Matrix of shortest hyperpaths lengths in the example

	n_{10}	n_{11}	n_{12}	n_{13}
n_1	–	2	2	2
n_2	–	1	1	1
n_3	–	–	–	1
n_4	–	2	2	2
n_5	–	–	–	–
n_6	–	2	3	3
n_7	–	1	2	2
n_8	1	3	1	4
n_9	–	2	2	2

Additional information about a hypergraph, for construction of transformation graphs, is provided by a matrix of shortest paths from product nodes to service nodes, such as one listed in Table 4.4. Shortest path values in Table 4.4 are calculated using the approach described in Section 4.3.2. The matrix of shortest hyperpaths provides insight into minimizing the number of used devices for the transformation graph. If the sought solution is such that the number of used devices is reduced to a minimum then the devices chosen from the hypergraph to form the transformation graph should lie on the shortest hyperpaths. Another piece of information provided in Table 4.4 indicates whether there is the option to deliver a service starting from a given product node, e.g. when investigating the first column it is clear that there is only one path between the product node n_8 and the service node n_{10}. Also, by looking at the third row it is clear that only the product n_3 is required to satisfy the service n_{13}. This could be an indication that, from the point of increasing resilience, it might be beneficial to add other devices that could deliver this service. Table 4.4 can also be used to highlight critical nodes or edges, i.e. the nodes or edges which, if removed, will prevent the required services from being delivered. Table 4.4 also shows that there are no paths between the product n_5 and any of the services. Thus, the product n_5 is not used as an input by any of the devices in this example. Apart from shortest hyperpaths between product nodes and service nodes, the matrix of shortest paths can be also used to investigate how one product can be converted into another, e.g. product n_6 can only be converted by device e_8 into the products n_5 and n_7. Whilst information contained in either one of the representations is sufficient to uniquely define a graph, the incidence matrix and the matrix of shortest hyperpaths offer different and complementary descriptions of a hypergraph.

Another crucial property of a node or edge is the *betweenness centrality*, also sometimes referred to as the *load*. It is a measure of centrality and describes the importance of a given node or edge in a network by quantification of the number of shortest paths that traverse this node [184].

$$C_i^{(b)} = \sum_{j \neq i \neq k} \frac{\sigma_{jk}(n_i)}{\sigma_{jk}}, \tag{4.5}$$

where $\sigma_{jk}(n_i)$ is the number of shortest paths between node n_j and n_k that pass through node n_i and σ_{jk} is the number of shortest paths between nodes n_j and n_k [185]. The measure of *betweenness centrality* is useful in identifying critical nodes and evaluation of the network's resilience to removal of certain nodes from the network, i.e. failures. A high value indicates that a node is essential and should not be removed In the case of utility–service provision the main issue is not the removal of certain nodes, but failure to deliver products that are represented by these nodes. Therefore, the problem can be considered as possibility of obtaining the product in case of the infrastructure failure.

Top betweenness nodes in the example are: electricity: $C_{n_1}^{(b)} = 0.216$, clean water: $C_{n_7}^{(b)} = 0.182$, greywater: $C_{n_6}^{(b)} = 0.083$. It shows that the highest number of shortest paths is traversing the electricity node since most of the devices presented in this example need electrical power to operate. However, since there are two devices, e_1 and e_9, that can produce electricity it is theoretically possible to deliver electricity to the system during a failure of a power grid. However, whether the amount of electricity provided from this second source is sufficient needs to be checked by calculating mass balances.

4.3.2 Shortest hyperpaths in Mastergraph

The shortest hyperpaths in Mastergraph represent a set of devices required to transform one product into another product or a service. The proposed algorithm (Figure 4.7) not only calculates the shortest hyperpaths lengths, but also lists all possible combinations of the same length. This gives an opportunity to explore various options when building the transformation graph. The algorithms runs until it finds the shortest hyperpath between selected source product and target product or service. The initial condition for the algorithm to start is at least one device that uses the source product as an input as well as at least one device that produces the target product or service. If one or both requirements are not met, the initial parameters must be changed.

The algorithm uses information stored in the XML database to search for

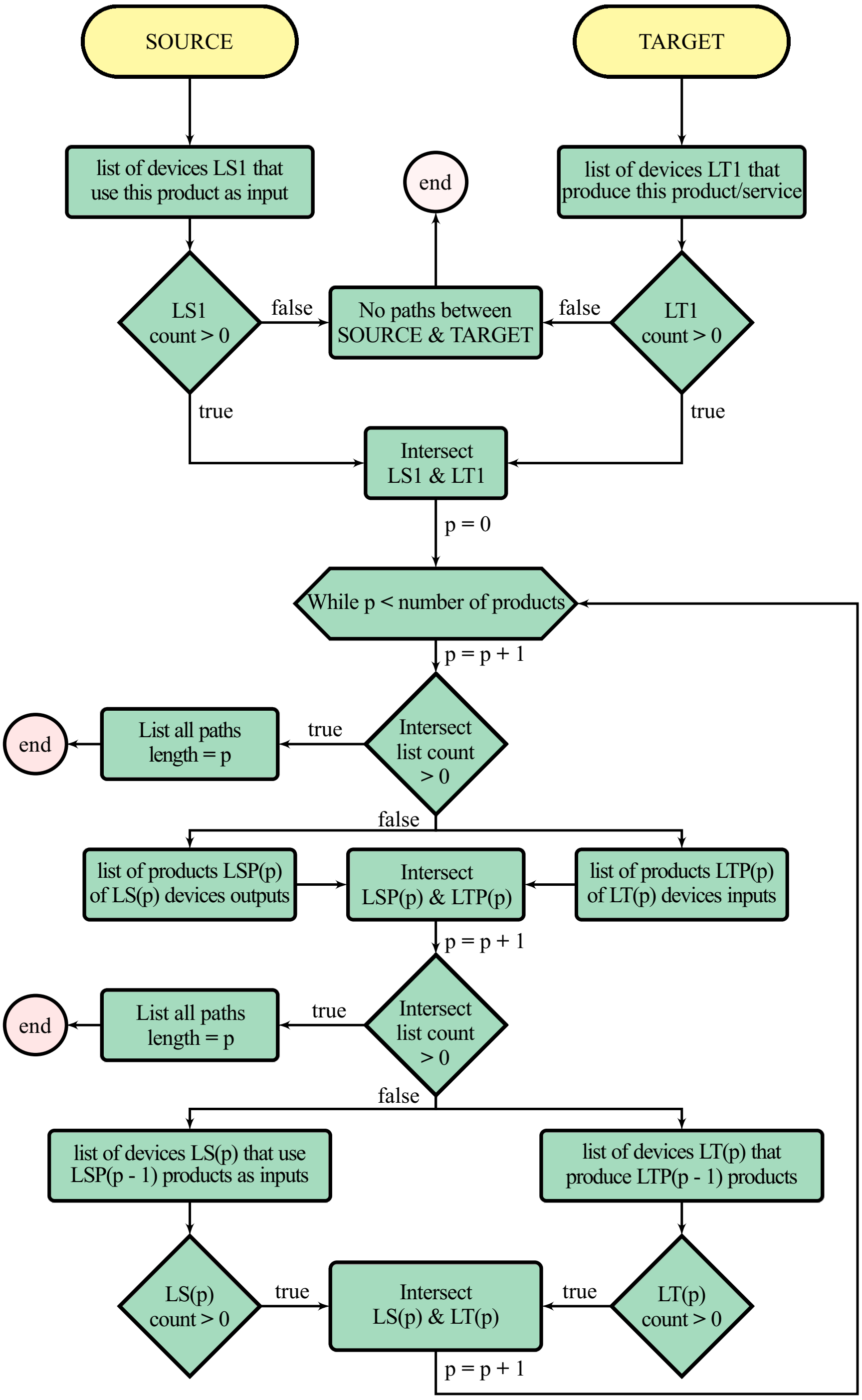


Figure 4.7: Shortest hyperpaths algorithm

appropriate devices to link two nodes: either product to product or product to service. The flowchart for the algorithm is presented in Figure 4.7. When the initial conditions are met, a list $LS1$ of devices that use the source product as an input is created as well as a list $LT1$ of devices that produce target product/service. The two lists are intersected. If there are the same devices in both list, the algorithm terminates as at least one hyperpath was found and its length is 1. If the intersection of the two lists is empty, additional two lists are created: (i) products $LSP1$ that are produced by all devices from list $LS1$ and (ii) products $LTP1$ that are used by all devices from list $LT1$ as inputs. In the next step the lists $LSP1$ and $LTP1$ are intersected. If there are any common devices in these two lists, the algorithm terminates, as at least one hyperpath was found and its length is 2. If the intersection of these two lists is empty, additional lists are created: (i) devices $LS2$ that use products from $LSP1$ as inputs and (ii) devices $LT2$ that produce products from $LTP1$. These two lists are intersected in order to find paths of lengths 3. The algorithm will repeat these steps creating new lists of products/devices until it finds the hyperpaths or until it reaches the length equal to the number of products in Mastergraph. The latter is equivalent to the fact that there are no paths connecting source product with target service.

The interface to calculate the shortest hyperpaths is embedded in the XML database content editor (Figure 4.8). It is divided into two parts: (i) the search for hyperpaths from a product to another product and (ii) the search for hyperpaths from a product to a service. For the example presented in Figure 4.8 there are no hyperpaths of length 1 from product *rain water* to product *drinking water*. However there are several hyperpaths of length 2, see Figure 4.8. All possible combinations are listed under: path length: 2. In the case of searching for a hyperpath from product *food* to service *nutrition* there are several hyperpaths of length 1. This corresponds to the fact that there are devices in the database that convert the source product into the target product directly.

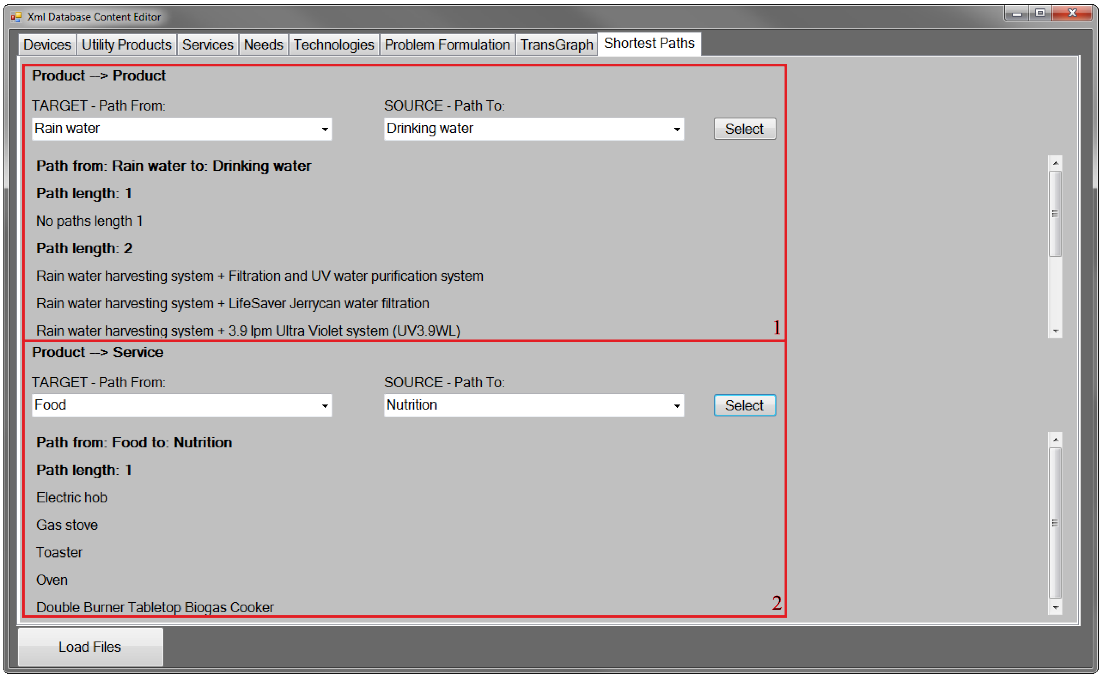


Figure 4.8: GUI for shortest hyperpaths calculation

Finding hyperpaths from a product to another product or a service has its limitations when it comes to finding “suitable” devices to be used in a transformation graph. It does not provide information about other products that are also required by the devices selected for the hyperpath. Therefore, in order to fully utilize this approach inputs and outputs of each device must be considered in order to select the most appropriate option to each situation.

4.3.3 Complete representation of the database

Mastergraph has the same structure as the simplified hypergraph presented in Section 4.3.1 but with a larger number of nodes and hyperedges. It is built using information about products, devices and services stored in the database. The complete Mastergraph corresponding to the current content of the database is presented in Figure 4.9. At the current state of development Mastergraph contains $N = 55$ nodes (products and services) and $E = 97$ hyperedges (devices). The size of Mastergraph is 299 with a device having, on average, 3.1 inputs and outputs. Mastergraph can be generated automatically in the simulation system (button marked as 8 in Figure 3.12). Additionally, the modified incidence matrix and two matrices that provide quantitative information about the operating rules of the devices (described in Section 4.3.1) are exported to XLS file. The matrices can be found in Appendix C.

The list of nodes corresponds to products and services. The edges in Mastergraph correspond to devices in the database. They are listed below for reference. The entire Mastergraph is presented in Figure 4.9 (additionally the Mastergraph is in Appendix C as a SVG file).

List of nodes in Mastergraph that represent services:

n_1	Full body cleaning
n_2	Thermal comfort - heating
n_3	Information access
n_4	Provision of drinking water
n_5	Nutrition
n_6	Electric car charger
n_7	Clothes cleaning
n_8	Water for Plant Watering and Outdoor Use
n_9	Removal of liquid waste
n_{10}	Partial body cleaning
n_{11}	Removal of solid waste
n_{12}	Washing dishes
n_{13}	Food storage
n_{14}	Food heating up

n_{15} Thermal comfort - cooling
n_{16} Humidification
n_{17} Entertainment
n_{18} Sufficient amount of light - artificial
n_{19} Ventilation
n_{20} Clothes drying
n_{21} Home gym
n_{22} Powering small electronic appliances

List of nodes in Mastergraph that represent products:

n_{23} Drinking water
n_{24} Grey water
n_{25} Electrical power
n_{26} Natural gas
n_{27} Information
n_{28} Food
n_{29} Organic waste
n_{30} Hydrocarbon transport fuel
n_{31} Biomass
n_{32} Carbon dioxide
n_{33} Biogas
n_{34} Seawater
n_{35} Groundwater
n_{36} Solar irradiation
n_{37} Rain water
n_{38} Compost
n_{39} Urine
n_{40} Diesel fuel
n_{41} Solid waste
n_{42} Ambient air
n_{43} Useful heat
n_{44} Illuminance
n_{45} Wind energy
n_{46} Nutritional artificially flavoured ink tubes
n_{47} Clean water
n_{48} Wastewater
n_{49} Domestic hot water
n_{50} Wave energy
n_{51} Hydrokinetic energy

n_{52} Sludge
n_{53} Hydrogen
n_{54} Sound pressure
n_{55} Thorium (Th-232)
n_{56} Fertigation Water

List of edges in Mastergraph that represent devices:

e_1 Shower with electric water heater
e_2 Ultrasonic shower
e_3 Gas space heater
e_4 Electric space heater
e_5 Electric hob
e_6 Gas stove
e_7 Toaster
e_8 Tap
e_9 Greywater recycler
e_{10} Electric car charger - Tesla Model X 20kW
e_{11} Dishwasher
e_{12} Treadmill
e_{13} Membrane-based desalination facility
e_{14} Air Fuel Synthesis system
e_{15} Electric car charger - 6.6KW
e_{16} Bath
e_{17} Anaerobic digester (plus ohmic heating)
e_{18} Modular Membrane BioReactor (MBR)
e_{19} Diesel Generator
e_{20} Boiler
e_{21} Hybrid GaAs-Nanowire-Carbon-Nanotube Flexible Photovoltaics
e_{22} Food printing
e_{23} Kitchen tap
e_{24} Rain water harvesting system
e_{25} Intelligent toilet
e_{26} Electric car charger
e_{27} Silicon Photovoltaic system
e_{28} In-situ food-waste composting
e_{29} Solid waste space heater
e_{30} Domestic dehumidifier
e_{31} Spray-on battery
e_{32} Ground source heat pump system

e_{33}	Wireless communication hub
e_{34}	Micro CHP using solid waste
e_{35}	Solar water heating systems
e_{36}	Washing machine
e_{37}	Tumble drier
e_{38}	Grey water re-user
e_{39}	Compact fluorescent lamp (CFL)
e_{40}	Light emitting diode (LED) lamps
e_{41}	Geothermal power generation with an Stirling engine
e_{42}	Liquefied molten salt thorium nuclear power generation
e_{43}	Urine purification
e_{44}	Three-blade wind turbine
e_{45}	Toilet basin tap
e_{46}	Air source heat pump
e_{47}	Micro-hydropower
e_{48}	Home aerobic wastewater treatment
e_{49}	Rain power generation
e_{50}	Solar powered deep well pumping systems
e_{51}	Sumerged oscillating wave energy converter
e_{52}	In-stream tidal flow energy converter
e_{53}	Domestic air conditioning unit
e_{54}	Cold plasma air conditioning - heating
e_{55}	Fridge
e_{56}	Freezer
e_{57}	Microwave oven
e_{58}	television LCD
e_{59}	Video games console
e_{60}	Filtration and UV water purification system
e_{61}	UVGI air cleaner
e_{62}	Oven
e_{63}	Dishwasher
e_{64}	Shower
e_{65}	Computer
e_{66}	WatAir - Water from thin air
e_{67}	Household Mini Hydro Turbine
e_{68}	Electro-coagulation wastewater treatment
e_{69}	Microbial fuel cell wastewater treatment and power generation
e_{70}	Ocean salinity power generation (reversed electro dialysis)
e_{71}	Organic photovoltaics
e_{72}	Hydrogen from urine

e_{73} Hydrogen from wastewater - microbial fuel cell
e_{74} Hydrogen from biomass - SyPaB
e_{75} Sonic electricity generation
e_{76} LifeSaver Jerrycan water filtration
e_{77} 3.9 lpm Ultra Violet system (UV3.9WL)
e_{78} Aquaco Residential Grey Water Recycling System
e_{79} Greywater recycler with BTM - service
e_{80} Greywater recycler with BTM - product
e_{81} Aquality - rainwater harvesting system
e_{82} Tap for outdoor use
e_{83} Recover - residential water recovery
e_{84} Toilet - clean water
e_{85} Bath with electric water heater
e_{86} Household sand filter
e_{87} Electrical Socket
e_{88} Solar Water Pump
e_{89} Solar water pump for irrigation
e_{90} Exercise bicycle with LCD display
e_{91} Anaerobic Digestion (Small-scale)
e_{92} Anaerobic Baffled Reactor (ABR)
e_{93} UASB Reactor
e_{94} Double Burner Tabletop Biogas Cooker
e_{95} Electricity Generator from Biogas
e_{96} Toilet

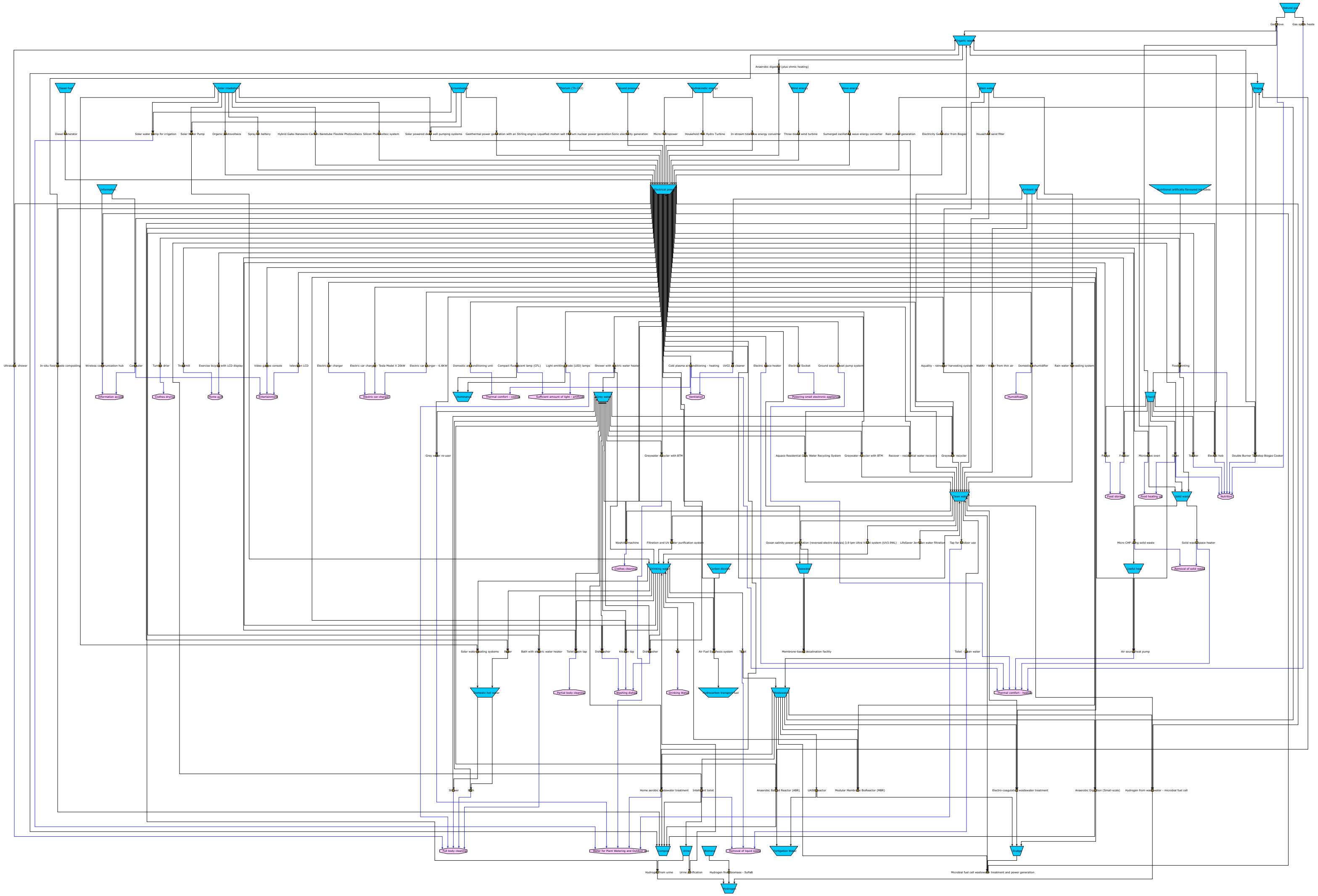


Figure 4.9: Complete Mastergraph

4.3.3.1 Critical nodes

Degree distributions of the nodes in Mastergraph considering individually inputs (in), outputs (out), are presented in Figure 4.10.

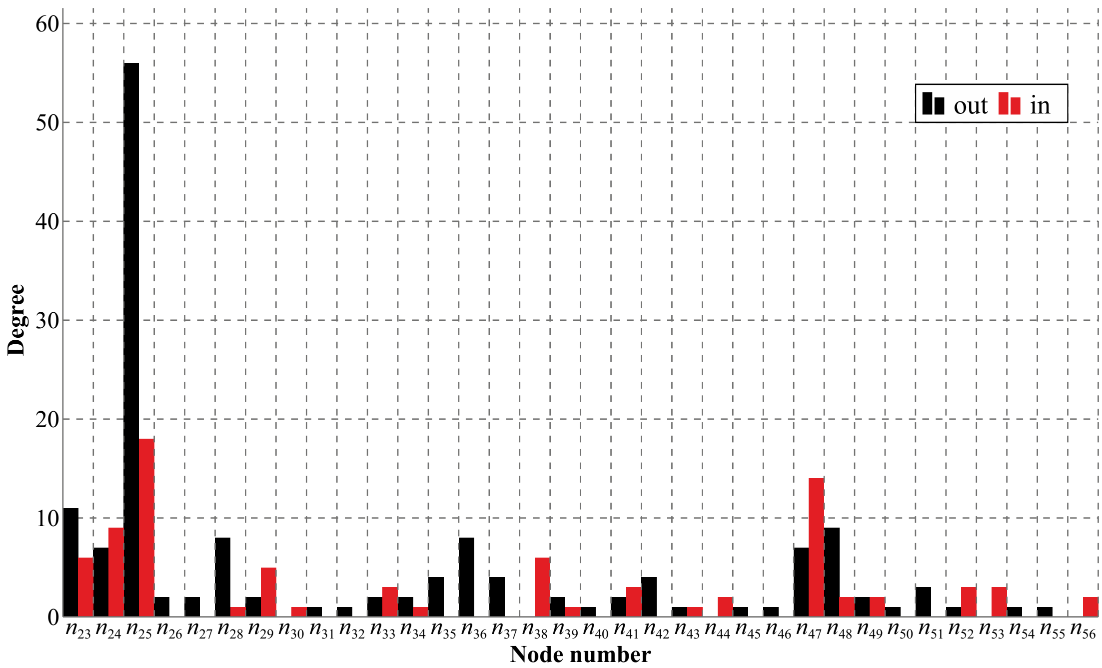


Figure 4.10: Degree distribution in Mastergraph. Nodes represent: n_{23} – Drinking water, n_{24} – Grey water, n_{25} – Electrical power, n_{26} – Natural gas, n_{27} – Information, n_{28} – Food, n_{29} – Organic waste, n_{30} – Hydrocarbon transport fuel, n_{31} – Biomass, n_{32} – Carbon dioxide, n_{33} – Biogas, n_{34} – Seawater, n_{35} – Groundwater, n_{36} – Solar irradiation, n_{37} – Rain water, n_{38} – Compost, n_{39} – Urine, n_{40} – Diesel fuel, n_{41} – Solid waste, n_{42} – Ambient air, n_{43} – Useful heat, n_{44} – Illuminance, n_{45} – Wind energy, n_{46} – Nutritional artificially flavoured ink tubes, n_{47} – Clean water, n_{48} – Wastewater, n_{49} – Domestic hot water, n_{50} – Wave energy, n_{51} – Hydrokinetic energy, n_{52} – Sludge, n_{53} – Hydrogen, n_{54} – Sound pressure, n_{55} – Thorium (Th-232), n_{56} – Fertigation Water

In Mastergraph the most connected nodes are: n_{25} – electricity (total: 76, in: 18, out: 58), n_{47} – clean water (total: 21, in: 14, out: 7), n_{23} – drinking water (total: 15, in: 6, out: 9), n_{24} – greywater (total: 18, in: 9, out: 7) and n_{48} – wastewater (total: 12, in: 3, out: 9). These parameters provide information that can be used to improve the robustness of transformation graphs in case of infrastructures' failures. In order to develop a resilient solution, nodes connected to the most connected nodes must be investigated. There are two types of nodes that must be considered: (i) nodes that represent products that will influence the feasibility of a transformation graph if they fail to be delivered by the infrastructure, and (ii) nodes that represent products that will influence the feasibility of a transformation graph if they fail to be removed by the infrastructure. Electricity and drinking water belong to the former group (i), and the remaining three belong to the latter (ii).

In the case of electricity there are 18 edges coming into the node and 58 edges leaving it. This corresponds to 18 devices that can produce electricity and 58 that require it to function. Out of these 58 devices, 36 deliver one or more services. Therefore, it is clear that alternative sources of electricity are of paramount importance if a resilient solution is to be proposed. These alternative sources could help households/communities to become independent to electric grid failures. At the current state of development there are 18 devices stored in the database that can produce electricity either from natural resources, such as rainwater, solar irradiation, groundwater, or from by-products such as solid waste, wastewater, greywater. However, ability to produce electricity is only a part of the solution. Advanced storage technologies are necessary for resilient solutions especially in the case of electricity. These technologies could help to increase use of renewable resources for electricity generation and make households/communities independent of the grid. Some of the storage solutions also enable storage of electricity supplied by the grid in an off-peak tariff, to be used when the rates are higher.

Clean water is directly connected to drinking water, as the majority of the devices in the database use the former to produce the latter. Therefore, both nodes are relevant while considering robustness of the utility–service provision network. Out of all devices using drinking water, 8 is responsible for delivering services directly. However, this number does not represent properly how important drinking water is in everyday life. Some of the devices stored in the database use clean water instead of drinking water, i.e. toilets, washing machines. Additionally, water obtained from natural resources, i.e. rainwater, is first converted into clean water and later treated to drinking quality.

Greywater and wastewater are also among the most connected nodes. They represent devices that are crucial in improving the current utility–service provision approach. In most cases these two products are removed by the infrastructure as waste products. However, they could be treated to clean water or drinking water and re-used in a household/community.

4.3.3.2 Shortest paths

The shortest paths provide useful information about whether there is a connection between certain nodes. The shortest paths lengths are calculated using the algorithm presented in Section 4.3.2. The shortest paths lengths between products and products are presented in Table 4.5 while the shortest paths lengths between products and services are presented in Table 4.6. They indicate what is the minimum number of devices required to convert one product into other product/service. Some of the nodes in the first column in Table 4.5 and Table 4.6 are missing due to the fact that there is no path between a node and a product/service.

Table 4.5: Shortest paths in Mastergraph between products and products. Nodes represent: n_{23} – Drinking water, n_{24} – Grey water, n_{25} – Electrical power, n_{26} – Natural gas, n_{27} – Information, n_{28} – Food, n_{29} – Organic waste, n_{30} – Hydrocarbon transport fuel, n_{31} – Biomass, n_{32} – Carbon dioxide, n_{33} – Biogas, n_{34} – Seawater, n_{35} – Groundwater, n_{36} – Solar irradiation, n_{37} – Rain water, n_{38} – Compost, n_{39} – Urine, n_{40} – Diesel fuel, n_{41} – Solid waste, n_{42} – Ambient air, n_{43} – Useful heat, n_{44} – Illuminance, n_{45} – Wind energy, n_{46} – Nutritional artificially flavoured ink tubes, n_{47} – Clean water, n_{48} – Wastewater, n_{49} – Domestic hot water, n_{50} – Wave energy, n_{51} – Hydrokinetic energy, n_{52} – Sludge, n_{53} – Hydrogen, n_{54} – Sound pressure, n_{55} – Thorium (Th-232), n_{56} – Fertigation Water

	n_{23}	n_{24}	n_{25}	n_{28}	n_{29}	n_{30}	n_{33}	n_{34}	n_{38}	n_{39}	n_{41}	n_{43}	n_{44}	n_{47}	n_{48}	n_{49}	n_{52}	n_{53}	n_{56}
n_{23}	0	1	2	3	2	1	2	3	2	2	3	4	3	2	1	1	2	2	2
n_{24}	2	0	2	3	1	3	1	2	1	3	3	4	3	1	2	3	3	3	1
n_{25}	1	1	0	1	1	1	1	2	1	1	1	2	1	1	2	1	1	1	2
n_{26}	4	4	3	4	1	4	2	5	2	4	4	5	4	4	5	4	4	4	5
n_{28}	3	3	2	0	1	3	2	4	2	3	1	2	3	3	4	3	3	3	4
n_{29}	3	3	2	3	0	3	1	4	1	3	3	4	3	3	4	3	3	3	4
n_{31}	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–
n_{32}	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–
n_{33}	2	2	1	2	1	2	0	3	2	2	2	3	2	2	3	2	2	2	3
n_{34}	2	2	1	2	2	2	2	0	2	2	2	3	2	1	2	2	2	2	3
n_{35}	1	2	1	2	2	2	2	2	2	2	2	3	2	1	2	2	2	2	3
n_{36}	1	2	1	2	2	2	2	2	2	2	2	3	2	1	2	1	2	2	3
n_{37}	2	2	1	2	2	2	2	2	2	2	2	3	2	1	2	2	2	2	3
n_{39}	1	2	3	4	3	2	3	4	3	0	4	5	4	3	2	2	3	1	3
n_{40}	2	2	1	2	2	2	2	3	2	2	2	3	2	2	3	2	2	2	3
n_{41}	2	2	1	2	2	2	2	3	2	2	0	1	2	2	3	2	2	2	3
n_{42}	2	2	2	3	3	3	3	2	3	3	3	4	3	1	2	3	3	3	3
n_{45}	2	2	1	2	2	2	2	3	2	2	2	3	2	2	3	2	2	2	3
n_{46}	3	3	2	1	2	3	3	4	3	3	1	2	3	3	4	3	3	3	4
n_{47}	1	1	1	2	2	2	2	1	2	2	2	3	2	0	1	2	2	2	2
n_{48}	1	1	1	2	2	2	1	2	1	1	2	3	2	1	0	2	1	1	1
n_{49}	3	1	3	4	2	4	2	3	2	4	4	5	4	2	3	0	4	4	2
n_{50}	2	2	1	2	2	2	2	3	2	2	2	3	2	2	3	2	2	2	3
n_{51}	2	2	1	2	2	2	2	3	2	2	2	3	2	2	3	2	2	2	3
n_{52}	2	2	1	2	2	2	2	2	2	2	2	3	2	1	2	2	0	2	3
n_{54}	2	2	1	2	2	2	2	3	2	2	2	3	2	2	3	2	2	2	3
n_{55}	2	2	1	2	2	2	2	3	2	2	2	3	2	2	3	2	2	2	3

Top betweenness is calculated using Equation 4.5. The nodes with the highest values are: electricity: $C^{(b)}_{n_{25}} = 0.4$, clean water: $C^{(b)}_{n_{47}} = 0.167$, greywater: $C^{(b)}_{n_{24}} = 0.092$, drinking water: $C^{(b)}_{n_{23}} = 0.083$. These values represent the fraction of all shortest paths in Mastergraph that go through the nodes. The highest value for the betweenness is for electricity as most devices stored in the database use it to operate.

Table 4.6: Shortest paths in Mastergraph between products and services. Nodes represent: n_1 – Full body cleaning, n_2 – Thermal comfort - heating, n_3 – Information access, n_4 – Provision of drinking water, n_5 – Nutrition, n_6 – Electric car charger, n_7 – Clothes cleaning, n_8 – Water for Plant Watering and Outdoor Use, n_9 – Removal of liquid waste, n_{10} – Partial body cleaning, n_{11} – Removal of solid waste, n_{12} – Washing dishes, n_{13} – Food storage, n_{14} – Food heating up, n_{15} – Thermal comfort - cooling, n_{16} – Humidification, n_{17} – Entertainment, n_{18} – Sufficient amount of light - artificial, n_{19} – Ventilation, n_{20} – Clothes drying, n_{21} – Home gym, n_{22} – Powering small electronic appliances, n_{23} – Drinking water, n_{24} – Grey water, n_{25} – Electrical power, n_{26} – Natural gas, n_{27} – Information, n_{28} – Food, n_{29} – Organic waste, n_{30} – Hydrocarbon transport fuel, n_{31} – Biomass, n_{32} – Carbon dioxide, n_{33} – Biogas, n_{34} – Seawater, n_{35} – Groundwater, n_{36} – Solar irradiation, n_{37} – Rain water, n_{38} – Compost, n_{39} – Urine, n_{40} – Diesel fuel, n_{41} – Solid waste, n_{42} – Ambient air, n_{43} – Useful heat, n_{44} – Illuminance, n_{45} – Wind energy, n_{46} – Nutritional artificially flavoured ink tubes, n_{47} – Clean water, n_{48} – Wastewater, n_{49} – Domestic hot water, n_{50} – Wave energy, n_{51} – Hydrokinetic energy, n_{52} – Sludge, n_{53} – Hydrogen, n_{54} – Sound pressure, n_{55} – Thorium (Th-232), n_{56} – Fertigation Water

	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}	n_{17}	n_{18}	n_{19}	n_{20}	n_{21}	n_{22}
n_{23}	1	3	3	1	3	3	3	2	1	1	4	1	3	3	3	3	3	3	3	3	3	3
n_{24}	3	3	3	3	2	3	2	1	2	3	4	3	3	3	3	3	3	3	3	3	3	3
n_{25}	1	1	1	2	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1
n_{26}	4	1	4	5	1	4	4	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4
n_{27}	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–
n_{28}	3	2	3	4	1	3	3	3	3	3	2	3	1	1	3	3	3	3	3	3	3	3
n_{29}	3	3	3	4	2	3	3	3	3	3	4	3	3	3	3	3	3	3	3	3	3	3
n_{33}	2	2	2	3	1	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{34}	2	2	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{35}	2	2	2	2	2	2	2	1	2	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{36}	2	2	2	2	2	2	2	1	2	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{37}	2	2	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{39}	2	4	4	2	4	4	4	3	2	2	5	2	4	4	4	4	4	4	4	4	4	4
n_{40}	2	2	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{41}	2	1	2	3	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2	2	2
n_{42}	3	1	3	3	3	3	2	2	2	3	4	3	3	3	3	1	3	3	1	3	3	3
n_{43}	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
n_{45}	2	2	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{46}	3	2	3	4	1	3	3	3	3	3	2	3	2	2	3	3	3	3	3	3	3	3
n_{47}	2	2	2	2	2	2	1	1	1	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{48}	2	2	2	2	2	2	2	1	1	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{49}	1	4	4	4	3	4	3	2	3	4	5	4	4	4	4	4	4	4	4	4	4	4
n_{50}	2	2	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{51}	2	2	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{52}	2	2	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{54}	2	2	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2
n_{55}	2	2	2	3	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2	2	2	2

Chapter 5

Case studies

5.1 Introduction

In this chapter the functionalities and capabilities of the simulation system are presented. In Section 5.2.1 a benchmark house developed based on the literature review of daily activities of users presented in Chapter 2 is analysed. Furthermore, alternative solutions were automatically generated using the developed simulation system. These solutions are compared based on their costs, as well as water and energy consumption. In Section 5.2.3 a case study is used to investigate whether it is possible to substitute all products delivered via separate infrastructures by one product. This case study is related to the “All in One” project and is representing a household in a community. The final case study presented in Section 5.3 analyses a household based in a rural community in Ilha Solteira in Brazil and presents possibilities for subsidising some of the demand from naturally available resources.

5.2 Case studies

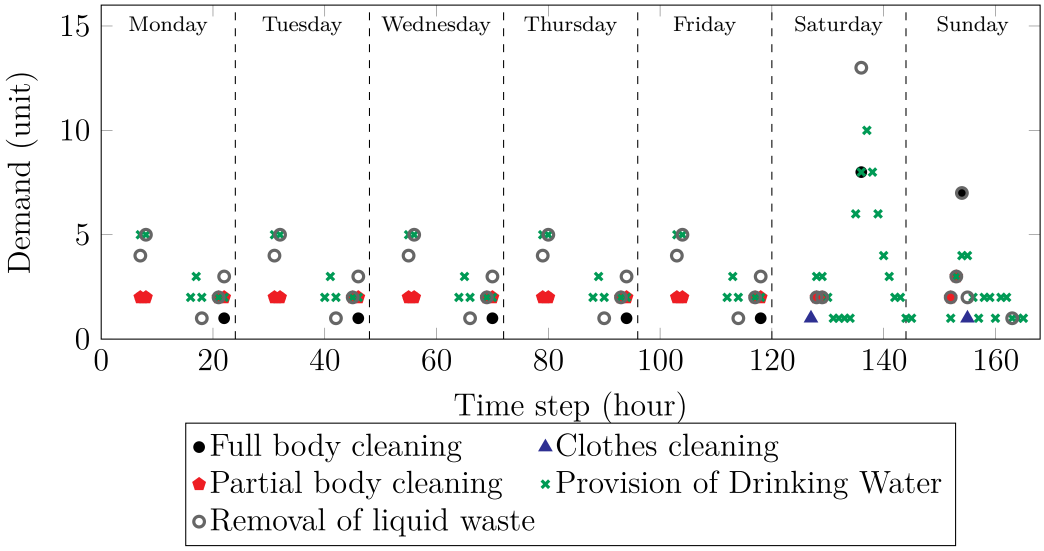
In the case studies presented in this Section a four person household is analysed. The time horizon for this case is 2017. The service demand are specified in Figure 5.1. In the following subsections different constraints on the products delivered/removed by the infrastructures are analysed. In Section 5.2.1 a benchmark solution is presented where all products are delivered and removed by the infrastructure, there is no recycling nor use of natural resources. All by-products are considered to be waste products and are removed by the infrastructure. In Section 5.2.2 the problem formulation is modified to include the use of naturally available resources as well as recycling of by-products. The alternative solutions are automatically generated using the approach presented in Section 4.2.2 and several scenarios are presented and discussed. Finally, in Section 5.2.3 a scenario is discussed where only one product can be delivered by the infrastructure. This example is connected to the “All in One” project. For definition of these solutions the shortest paths algorithm described in Section 4.3.2 is used in order to build transformation graphs.

5.2.1 Benchmark household

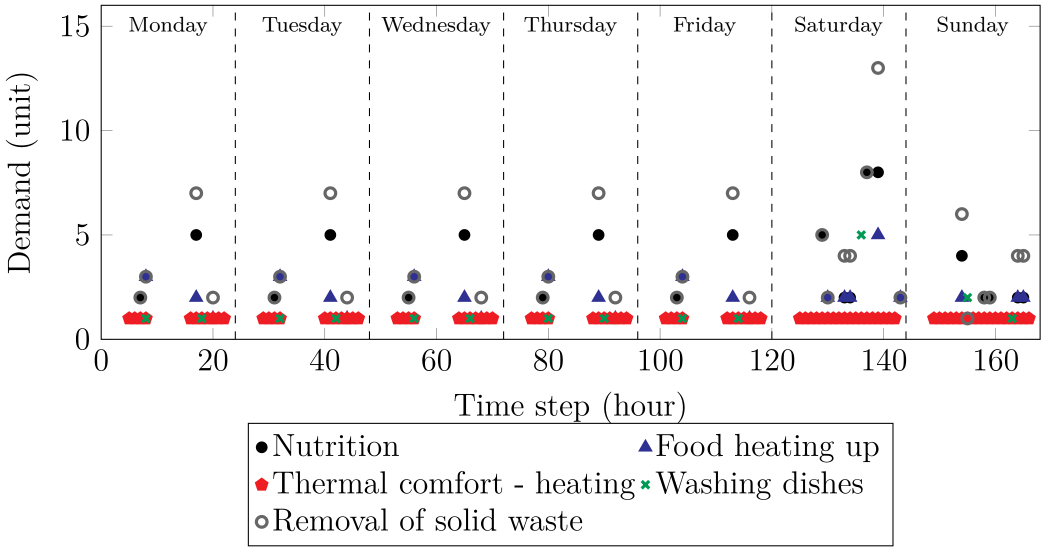
The problem formulation for this example is in Appendix C. There is a certain demand during weekdays as residents go to work; during the weekend the demand for most services is higher. Among the services required there are: full body cleaning, partial body cleaning, nutrition, provision of drinking water, removal of liquid/solid waste and others. They can be satisfied by use of everyday devices such as showers, baths, taps, heaters, etc. However, devices that can be used for recycling, i.e. conversion devices are important. They can be used to minimise the amount of water that has to be delivered to households, or subsidise part of energy demand from natural resources. For each case a transformation graph was created manually. It is a graph that contains all services that are required, devices that are needed to deliver these services or needed for recycling, and finally storages for each product used. In a transformation graph each node is either a device, a storage or a service and each edge is a product or a service carrier.

Product supplied by infrastructures are: drinking water (with associated cost of £1.5288 per cubic metre [186]) and electricity (with associated cost of £0.125 per kWh). Products that can be removed by the infrastructure are: greywater and wastewater (with associated cost of £1.6952 per cubic metre [186]). The cost of food is not considered in this case study it comes from different sources and, in most cases, is not delivered to households via infrastructures. All solid waste products do not have an associated cost due to the fact that in the UK this cost is included in the council tax that each household must pay. Figure 5.4 presents a candidate solution for the demand specified in Figure 5.1. This transformation graph was created manually to using information stored in the XML database. This solution is compared in Section 5.2.2 with four alternative scenarios (**A**, **B**, **C**, **D**). The benchmark solution is referred to as Scenario **X** in this chapter.

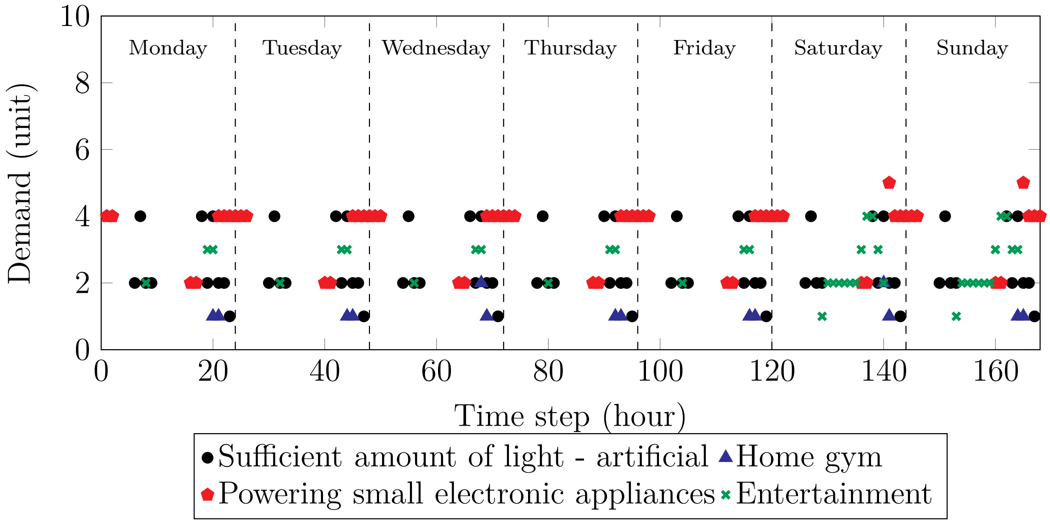
The service devices were selected randomly based on the available products defined in the problem formulation. In this transformation graph there are no storages, i.e. the storages have capacity of 0. The summary of cost, energy and water consumption is presented in Table 5.1.



(a)



(b)



(c)

Figure 5.1: Service demand

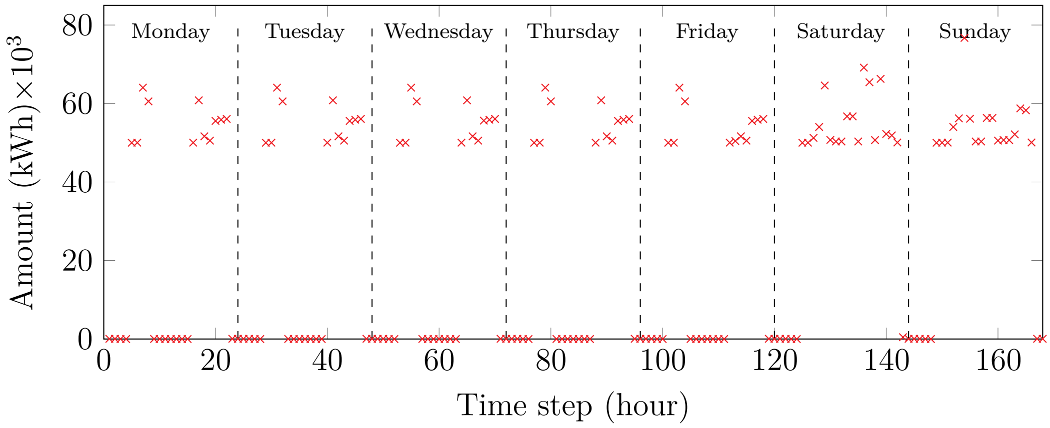


Figure 5.2: Electricity supplied in the benchmark caste study

Table 5.1: Summary of the benchmark (values related to one week)

Supply cost (£)	Remove cost (£)	Water supplied (litres)	Energy supplied (kWh)
8.83	5.29	4034	49.86

The drinking water consumption in the seven day period is 4034 litres, which corresponds to about 144 litres per person per day, which is consistent with the data presented in Section 2.3.2 - Table 2.2. The energy consumption is 49.86 kWh per week, which roughly gives a total of 1.78 kWh per person per day, which corresponds to the values presented in Section 2.3.1 - Table 2.1. Electricity is the only source of energy in the considered example. The total electricity demand for the period of one week is presented in Figure 5.2.

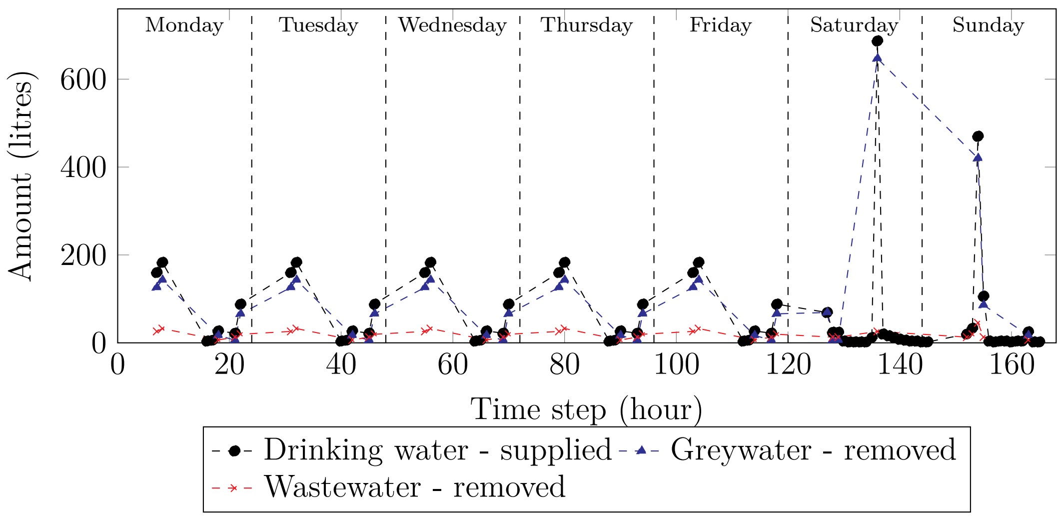


Figure 5.3: Products supplied & removed in the benchmark caste study

The total cost of supplying products and removing waste products is £14.12. The final amounts of drinking water delivered at each time step as well as greywater and wastewater removed at each time step are presented in Figure 5.3. The amounts of greywater and wastewater that must be removed at each time step

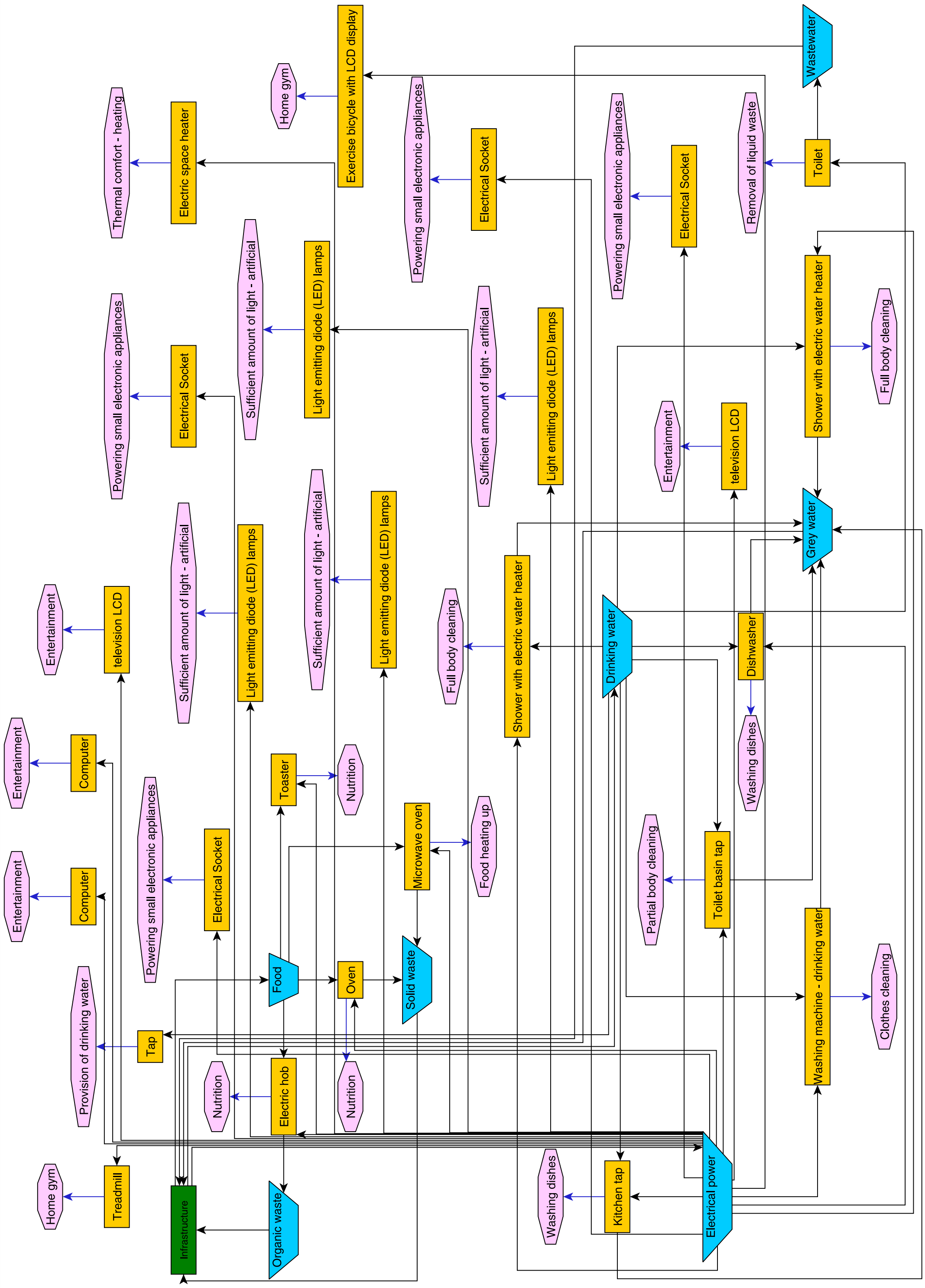


Figure 5.4: Transformation graph for the benchmark case study

correspond to the amount of drinking water supplied. Most of the drinking water is used for personal hygiene and washing up; only a fraction is consumed.

In this case all products produced are considered to be waste products and are removed by the infrastructure. By-products from service devices devoted to nutrition are organic and solid waste offer a possibility for conversion of these products into other, possibly more useful products. Greywater and wastewater can be recycled or treated to drinking water quality. These possibilities are analysed in Section 5.2.2.

5.2.2 Automatically generated alternative solutions

The main aim of the automatic generation of transformation graphs to a given utility–service provision problem is to consider alternative approaches to the current solutions. These approaches can involve the use of naturally available resources, as well as recycling of some by-products that usually are considered to be waste products and are removed by the infrastructure. The considered example includes rainwater. The amounts available in the time horizon (one week) are presented in Figure 5.5. The values for rainfall are theoretical and are based on the fact that 'moderate rain' is consider for 0.5 to 4 litres/h and 'heavy rain' is considered for values higher than 4 litres/h [187]. In the considered scenario the amounts available are defined as litres per square metre. Therefore, the processed amounts depend on the total area of the devices used to convert this products. Additionally, all clean water, wastewater and greywater can be recycled. Organic and solid waste can be removed from the system. The transformation graphs are assessed based on the final costs as well as energy and water consumption. The solution(s) considered the most sustainable, will be the one(s) that have a balance between the cost and the amounts of products that must be delivered/removed by the infrastructure.

The number of devices that can deliver required services in this case study is presented in Table 5.2.

Taking only the service devices the developed algorithm for automatic generation would find 77600 transformation graphs that satisfy the service demand. If there were no constraints on the products that can be used in the solution, almost 80 thousand transformations graphs would have to be taken into account. From such a large number it would be difficult to find the most appropriate solution. However, based on the products that can be delivered/removed from the infrastructure as well as the operational rules of devices, this number was limited significantly to over 5500 solutions. All feasible transformation graphs are

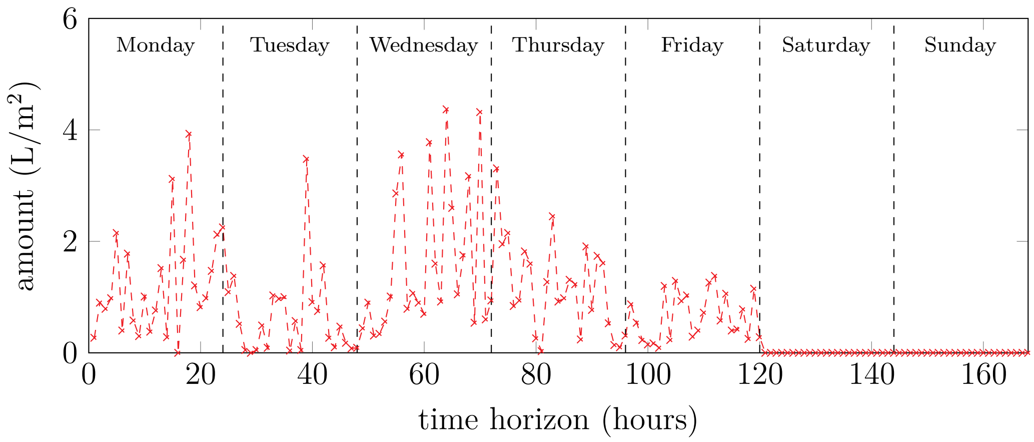


Figure 5.5: Rainfall intensity

Table 5.2: Service device availability

Service	Number of available devices
Full body cleaning	5
Thermal comfort - heating	6
Provision of drinking water	1
Nutrition	6
Clothes cleaning	2
Partial body cleaning	1
Washing dishes	3
Food heating up	2
Entertainment	3
Sufficient amount of light - artificial	2
Home gym	2
Powering small electronic appliances	1
Removal of liquid waste	3

exported in several outputs:

– a CSV file containing all transformation graphs listing all service and conversion devices as well as overall cost, water and energy consumption for the simulation horizon;
– XML files for each transformation graph in the format used for simulations;
– a GraphML file for each transformation graph for visualisation purposes. The file is consistent with yEd software.

Figure 5.6 presents the relationship of the overall cost, water and energy consumption for the automatically generated transformation graphs during the simulation horizon. Additionally, Figures 5.7-5.9 present relationships between energy and water supplied by the infrastructure, energy supplied and the total cost of each solution, and water supplied and the total cost of each solution. Four transformation graphs were selected for further analysis (indicated in Figures 5.6-5.9 by appropriate letter):

A – rainwater is not collected; greywater is treated to clean water quality and to drinking water quality.

B – rainwater is collected and treated; greywater is treated to drinking water quality; electricity comes only from the infrastructure.

C – rainwater is not collected; water demand is reduced by using alternative delivery of personal hygiene needs.

D – solid waste as well as rainwater are used to produce electricity; drinking water comes only from the infrastructure.

These four cases are analysed later.

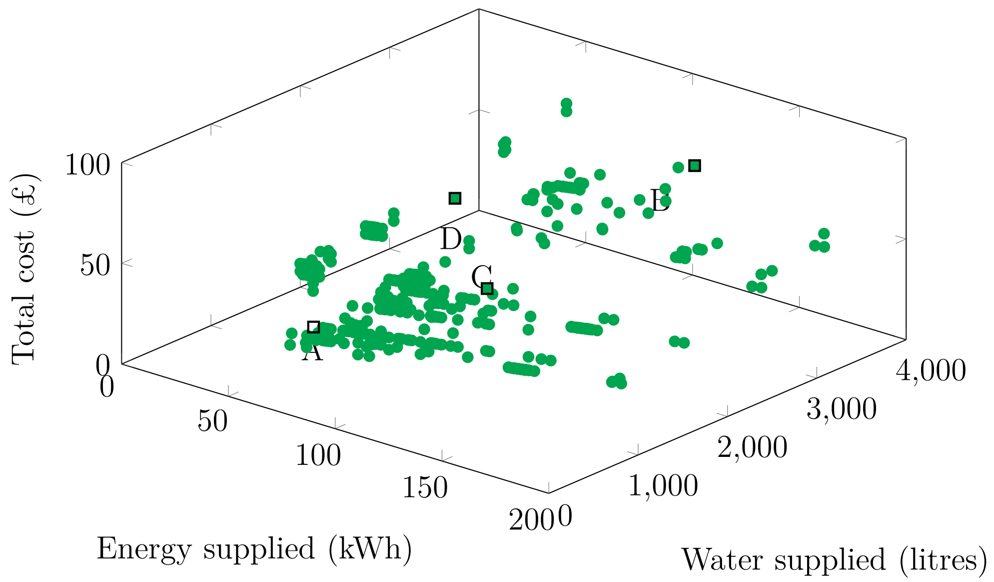


Figure 5.6: The relationship between cost, water and energy supplied for automatically generated transformation graphs

Figure 5.7 shows the relationship between the final amounts of energy and water supplied by the infrastructure for the whole simulation horizon. It indicates that the majority of automatically generated transformation graphs are located between 1000 and 2000 litres of water supplied and between 40 and 160 kWh of energy supplied. There is also a number of transformation graphs that are more water intense in relation to the water supplied by the infrastructure, i.e. they are located between 3000 and 4000 litres and similar amounts of energy supplied. This might be resulting from limited water recycling and selection of more water intense service devices.

Figure 5.8 presents the relationship between energy supplied by the infrastructure and the total cost of each solution. Majority of the solutions follow

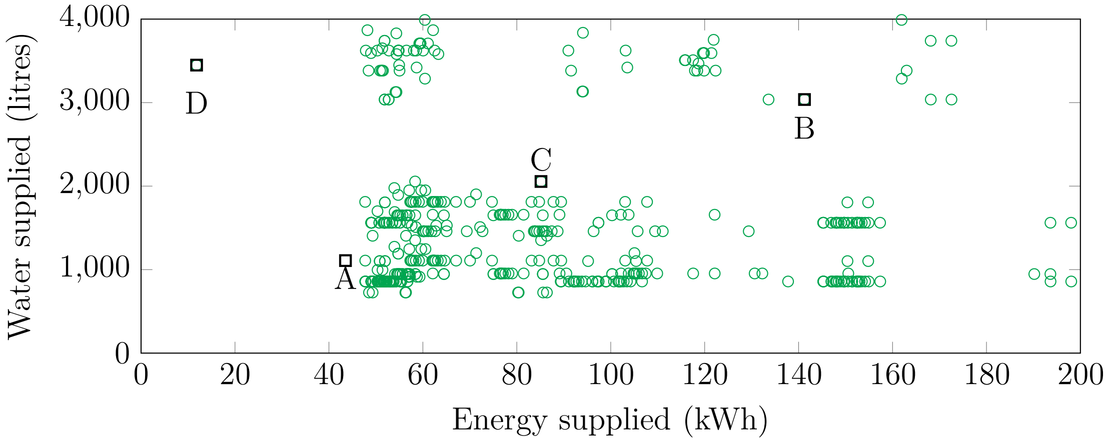


Figure 5.7: The relationship between energy and water supplied for automatically generated transformation graphs

two linear trends suggesting that increase in the amount of energy supplied is proportional to the cost. However, some of the solutions have overall energy consumption of about 50kWh, but the cost is spanning between £10 and £75 suggesting that there might be high cost of the products that must be removed by the infrastructure or large amount of water delivered by the infrastructure. However, since the cost of product removal is higher than the supply cost, it suggests the former explanation.

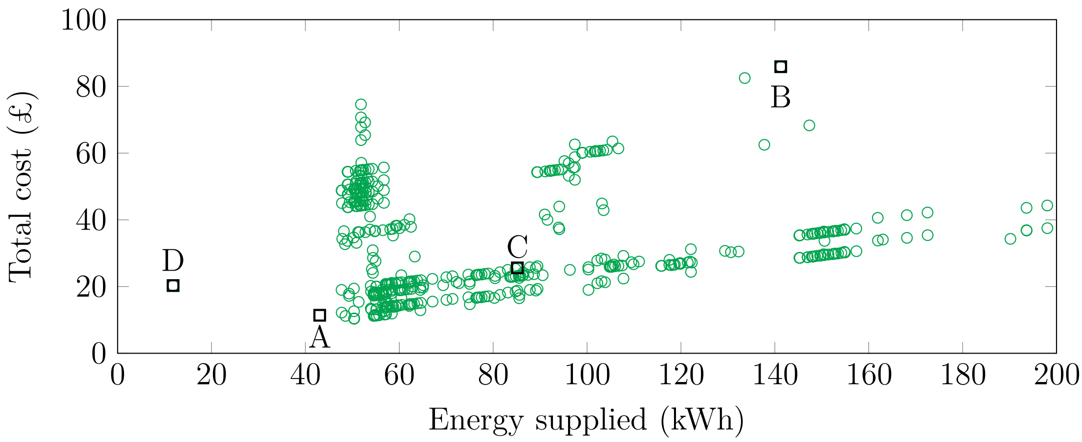


Figure 5.8: The relationship between energy supplied and cost for automatically generated transformation graphs

Figure 5.9 presents the relationship between water supplied by the infrastructure and the total cost of each automatically generated solution. It is clearly visible that for the same amounts of water delivered by the infrastructure there are various total costs. This would indicate that the main difference between the solution is their energy intensity or the cost of removing products by the infrastructure. The majority of the solutions fall between 750 and 2000 litres per week and 3000 and 4000 litres per week. Almost for all specific amounts of water supplied there are many different total costs of solutions that vary between £10 and £80.

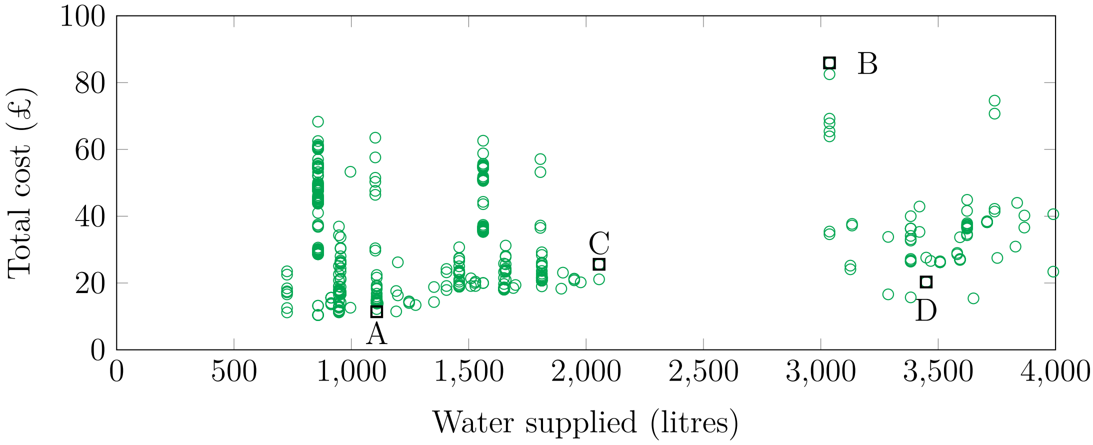


Figure 5.9: The relationship between water supplied and cost for automatically generated transformation graphs

The cumulative data for the four selected scenarios together with the benchmark (marked as **X**) is presented in Table 5.3

Table 5.3: Summary of the scenarios (per week) and average values per person per day

Scenario	Total cost (£/week)	Water supplied (litres/week)	Energy supplied (kWh/week)	Water supplied (litres/p/day)	Energy supplied (kWh/p/day)
A	11.4	1108	43.05	39.6	1.54
B	85.9	3037	141.25	108.5	5.04
C	25.6	2055	85.15	73.4	3.04
D	20.3	3449	11.8	123.2	0.40
X	14.12	4034	49.86	144.4	1.78

It is worth noting that the daily values presented in Table 5.3 do not refer to the daily consumption. In all cases water and/or energy is either subsidised from natural resources, recycled, converted to other products or all of the aforementioned. These values only present the amounts of water and energy supplied by the infrastructure. Similarly, the total cost of the solution refers only to the cost of supplying and removing products by the infrastructure. It does not take into account the investment costs needed to install all devices, modify the infrastructure if needed or the exploitation costs of these solutions. This can be potentially misleading as the supply/remove cost might be low, but otherwise it might be quite expensive. This is outside of the scope of the research presented in this thesis, but in the future should be taken into account.

Scenario A

The transformation graph is presented in Figure 5.10. In this transformation graph 25 service devices are used; there are 4 conversion devices used. In this scenario total amount of water supplied by the infrastructure is 1108 litres. Some of the demand for drinking water comes from recycling greywater and clean water. The total amount of energy supplied by the infrastructure is 43.05 kWh. This number is very similar to the benchmark case study. However, in this scenario solid waste is used to produce electricity to use locally. This helps to alleviate the energy demand for the conversion devices used to treat water either to clean or drinking water quality. Electricity is not stored - it is used immediately. Additionally, in this transformation graph natural gas is used for space heating and cooking. The associated supply cost per kWh is 2.78 pence [188].

In this solution the demand for drinking water supplied by the infrastructure is the lowest of the four scenarios and the benchmark. This is resulting not only from the fact that the water is treated, but also from the type of wet devices used, i.e. washing machine used in this solution requires clean water to operate, which reduces the amount of drinking water needed to be supplied by the infrastructure by about 140 litres per week with the defined demand. This saves on average 5 litres of water consumption per person per day. However, as only 1108 litres of drinking water is delivered by the infrastructure, the remaining 2786 needed to satisfy the demand for a week comes from treating greywater and clean water. With this approach the daily drinking water that is delivered by the infrastructure drops down to a very low number of 40 litres per person. In order to enable the recycling of all three products: drinking water, greywater and clean water have associated storages of a capacity 500 litres each.

This solution is cheaper than the benchmark (refer to Table 5.3). The main reason for that is the overall lower amounts of water and energy supplied by the infrastructure. Additionally, since only wastewater is removed from the household, the removal cost of products is the smallest amongst the scenarios. It is equal to £3 in a 7 day period.

This solution shows the potential of significant reduction of the amount of drinking water supplied by the infrastructure by recycling water within the household. However, this raises a question of additional non potable water distribution network needed to be installed in order for this solution to be feasible. It requires not only a substantial investment costs to introduce this new network for non potable water, but it could potentially require adjustments in the structure and design of the household. Moreover, the storages for products as well as conversion devices required for these processes also need significant amount of space.

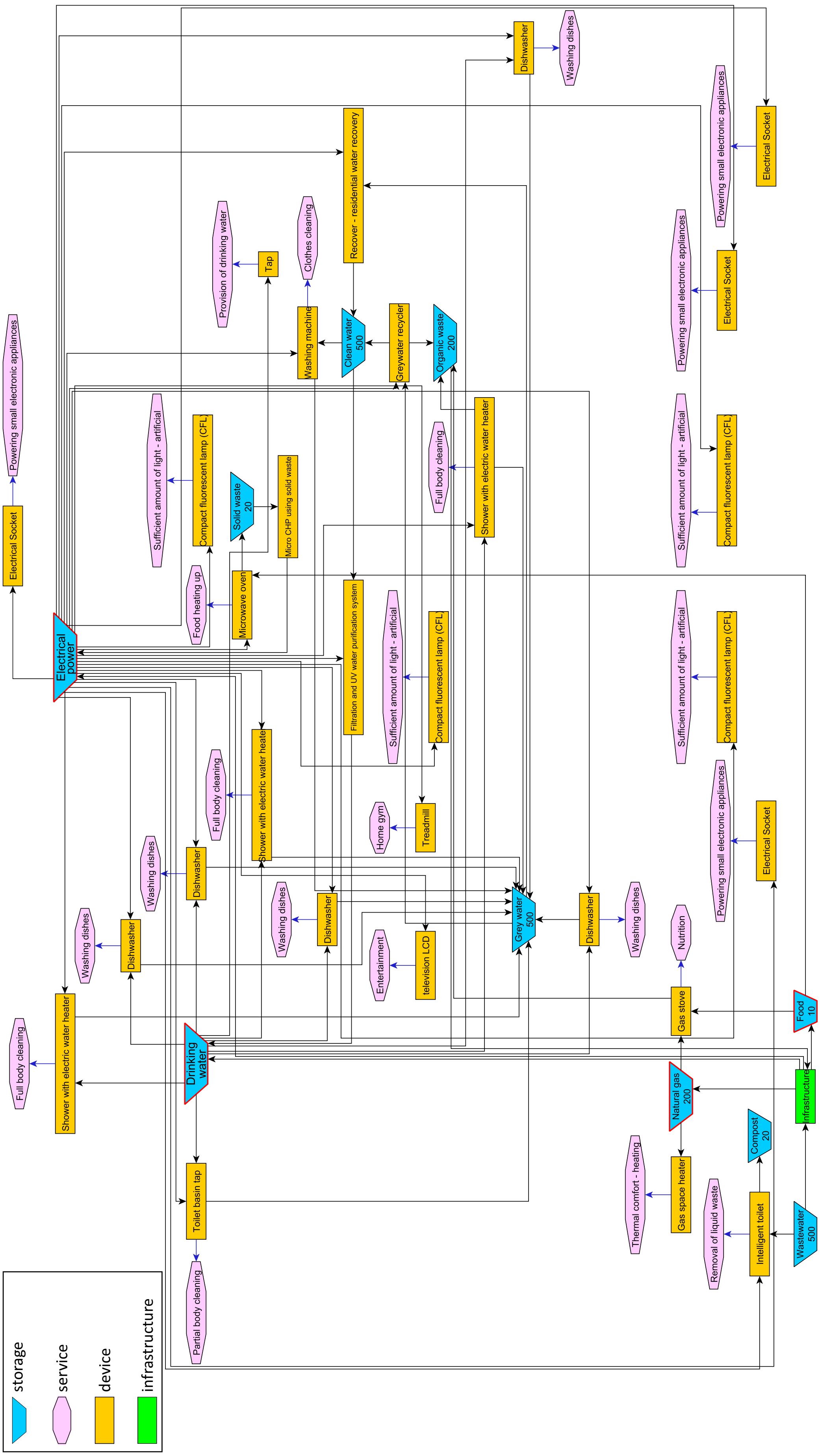


Figure 5.10: Transformation graph for Scenario A

Scenario B

The transformation graph is presented in Figure 5.11. In this transformation graph 26 service devices are used; there are 3 conversion devices used. In this scenario rainwater is collected and treated to drinking water quality. Additionally, some of produced greywater is treated to clean water which in turn is converted to drinking water. Electricity comes only from the infrastructure and is used for majority of devices. Natural gas is used for space heating only.

The total amount of drinking water supplied by the infrastructure is 3037 litres which corresponds to about 108 litres per person per day. This solution requires less than 1000 litres of drinking water to be supplied by the infrastructure compared to the benchmark case study. This is a result of using different service devices in this solution as well as the treatment of rainwater and greywater. In this scenario toilets are using clean water for flushing instead of drinking water. This alone reduces the demand for drinking water by more than 600 litres in a week. The weekly drinking water consumption in this scenario is 3430 litres. When comparing this to the amount of drinking water supplied by the infrastructure it is clear that almost 400 litres comes from other sources. All available rainwater (120 litres) is converted to drinking water and 873 litres of greywater is converted to clean water. Majority of that clean water is used for toilet flushing while about 250 litres is further treated to drinking water quality.

Greywater, clean water and drinking water have associated storages with 500 litres capacity each. This allows to significantly reduce the amount of drinking water that must be supplied during the times with no rainfall (from time step 121 to 168, i.e. most of Saturday and Sunday).

This solution is energy intensive. It is almost three times higher than the energy demand in the benchmark (marked as scenario X in Table 5.3). The amount of energy delivered from the infrastructure is equal to 141.25kWh. This is mainly caused by the need to treat rainwater and some of greywater to drinking water quality. These processes require more than half of the energy supplied. Additionally, energy is not subsidised from natural resources.

This solution is the most expensive amongst all scenarios (refer to Table 5.3) due to the increased demand for energy required for treating greywater to drinking quality. All wastewater and some of greywater produced in this scenario are removed from the system without recycling which increases the overall cost. Organic waste and solid waste produced when satisfying the need for nutrition are also removed from the system without recycling. The removal cost of all products is £27.1 which is the highest in all considered scenarios.

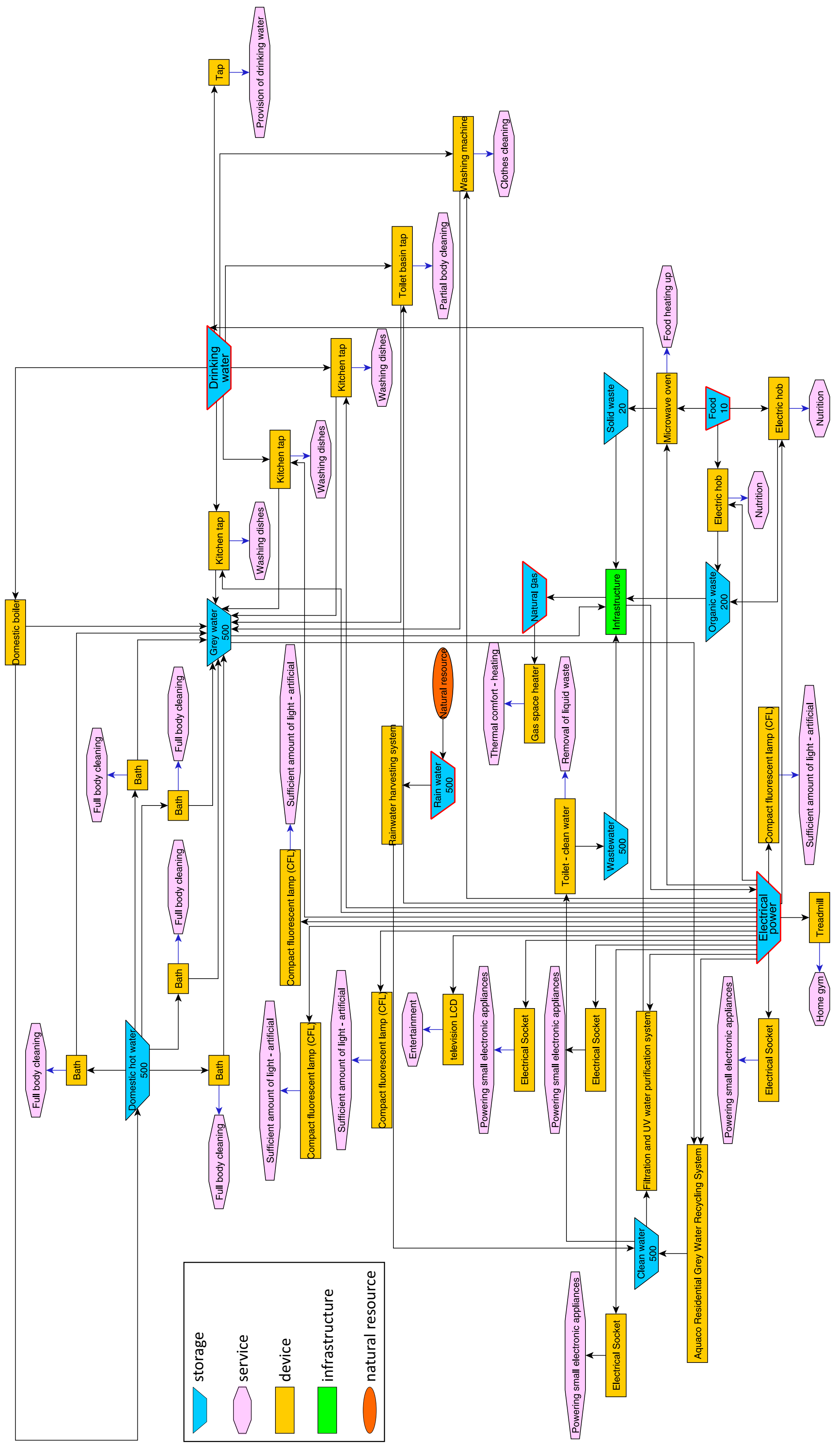


Figure 5.11: Transformation graph for Scenario B

Scenario C

The transformation graph for this scenario is presented in Figure 5.12. It consists of only 1 conversion device and 27 service devices. The amount of water delivered by the infrastructure is 2055 litres (in a week). This is almost half the amount delivered in the benchmark case study. The savings come from the fact that some of the greywater is recycled. Additionally, washing machine used in this scenario uses clean water which is obtained via recycling of greywater.

Devices used for satisfying personal hygiene need are mostly based on electricity - i.e. ultrasonic showers that use sonic pulse vibrations to remove dirt from human body. This technology does not require the use of water. Drinking water is only used for consumption, some of the personal hygiene needs and cleaning needs. In this scenario rain water is not collected.

This scenario is the second lowest with regards to the amount of drinking water delivered by the infrastructure amongst the scenarios. It almost halves the amount of water delivered in the benchmark in the considered time period, i.e. per capita consumption per day is equal to 73.4 litres compared to 144.4 litres. Drinking water consumption is also lower in this scenario due to unusual technology used for satisfying personal hygiene needs.

The shift from water-based approach towards satisfying personal hygiene needs saves 1680 litres of drinking water in a week's time compared to the solutions used in the benchmark case study. The remaining 300 litres difference comes from using devices that use clean water opposed to drinking water as an input.

The amount of energy supplied by the infrastructure is the second highest amongst the scenarios. The high demand comes from the fact that devices used for satisfying personal hygiene are energy intense. Additionally, electricity is required to convert greywater to clean water. Natural gas is used for heating, while electricity is used to satisfy all remaining needs. Moreover, neither the natural resources nor by-products are not used to produce energy locally. These result in almost doubling the amount of energy required in a week compared to the benchmark. All these factors result in a second highest supply cost (£16.5).

In this scenario organic waste, solid waste and wastewater are not converted into other products, hence they are removed by the infrastructure. The removal cost of these products is £9.1 per week. The initial investment for this solution would be substantial. Additionally, there would be a massive demand for space not only for the devices, but also for the storages. Each product in the transformation graph has a large capacity storage assigned to it.

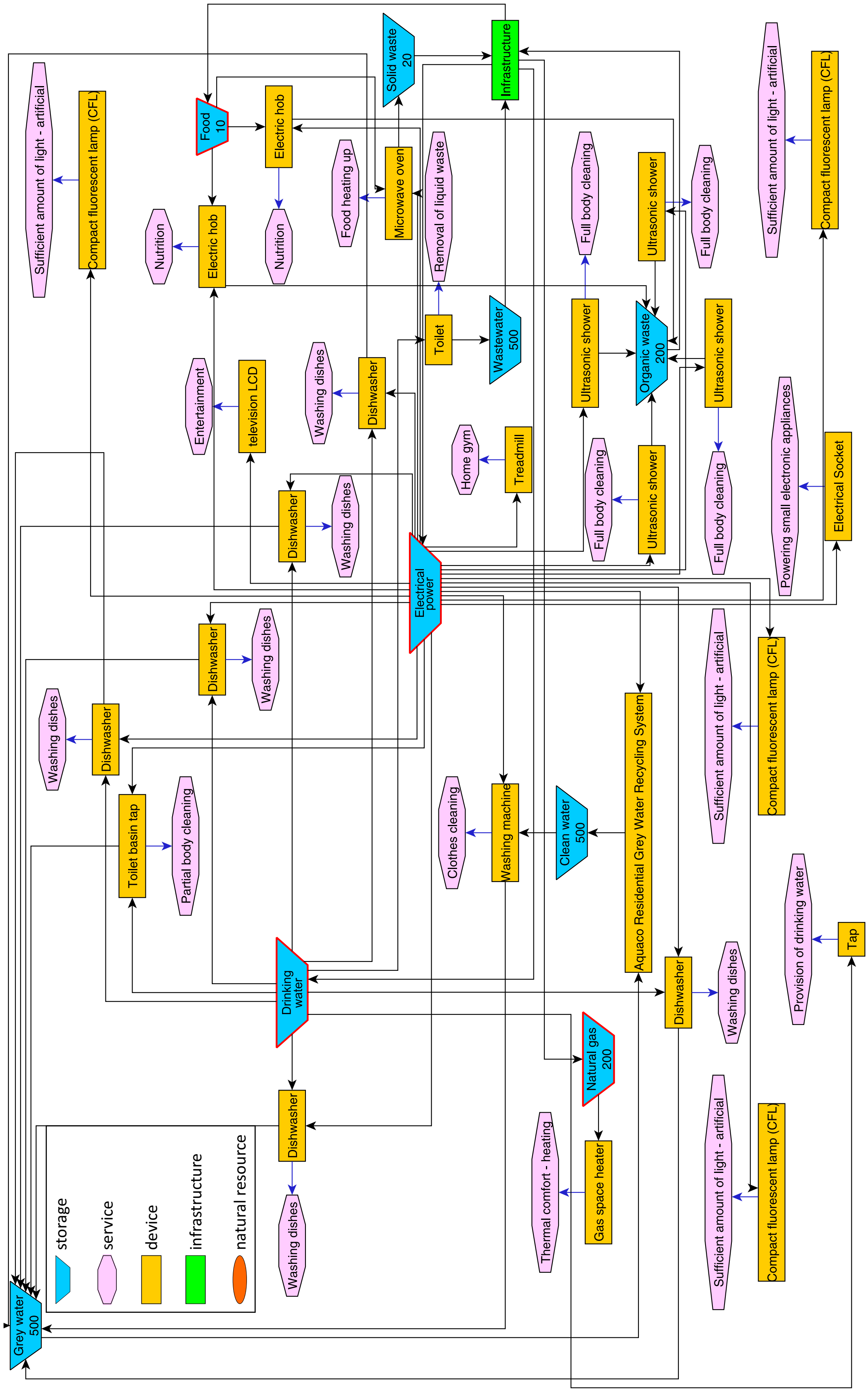


Figure 5.12: Transformation graph for Scenario C

Scenario D

The transformation graph is presented in Figure 5.13. It consists of 4 conversion devices and 27 service devices. In this scenario the lowest amount of energy is delivered by the infrastructure compared to all considered scenarios. The low amount of energy supplied in this solution comes from the fact that all four conversion devices are used to produce electricity. Moreover, drinking water is delivered directly from the infrastructure and it is not obtained from recycling or from natural resources.

In this scenario the lowest amount of energy is delivered by the infrastructure. The weekly demand for energy that is supplied by the infrastructure is 11.8 kWh. This value is four times smaller than the amount of energy supplied by the infrastructure in the benchmark (see Table 5.3). Some of the electricity demand is met by on-site generation. Rainwater, greywater and solid waste are used for this purpose. Rainwater is used to produce electricity via *rain power generation*. This rainwater is then collected in greywater storage. Greywater is then used to generate electricity via *Household Mini Hydro Turbine* device. Solid waste is burned using *Micro CHP using solid waste* to produce electricity. In this scenario electricity is stored locally and used when there is demand for it.

In this scenario the highest amount of drinking water must be supplied by the infrastructure amongst the four automatically generated cases. This results from the fact that no drinking water is obtained on-site. It is almost 600 litres lower than the benchmark case study. This saving is due to use of toilets that do not use drinking water for flushing. Per capita consumption is 123.2 litres per day. This is on average 20 litres lower than the benchmark case study.

The supply cost of all products is £5.5 (in a week) while the removal cost is equal to £14.8 (in a week). Although greywater is used for producing electricity it still must be removed from the household.

This solution is very close to scenario B when it comes to the amount of drinking water supplied by the infrastructure (with the difference of 412 litres). However, the amount of energy supplied by the infrastructure in scenario B is almost 12 times higher. This, in turn, contributes to the very high overall cost of that scenario. These factors indicate how energy intense is conversion of graywater and clean water into drinking water. Similarly, this scenario can be compared to scenario C from the overall cost perspective. Although the amount of energy supplied in scenario C is almost eight times higher, the difference in cost is only £5.3 (with scenario D being the cheaper one). This is a direct result of an increase in the amounts of waste products in scenario D.

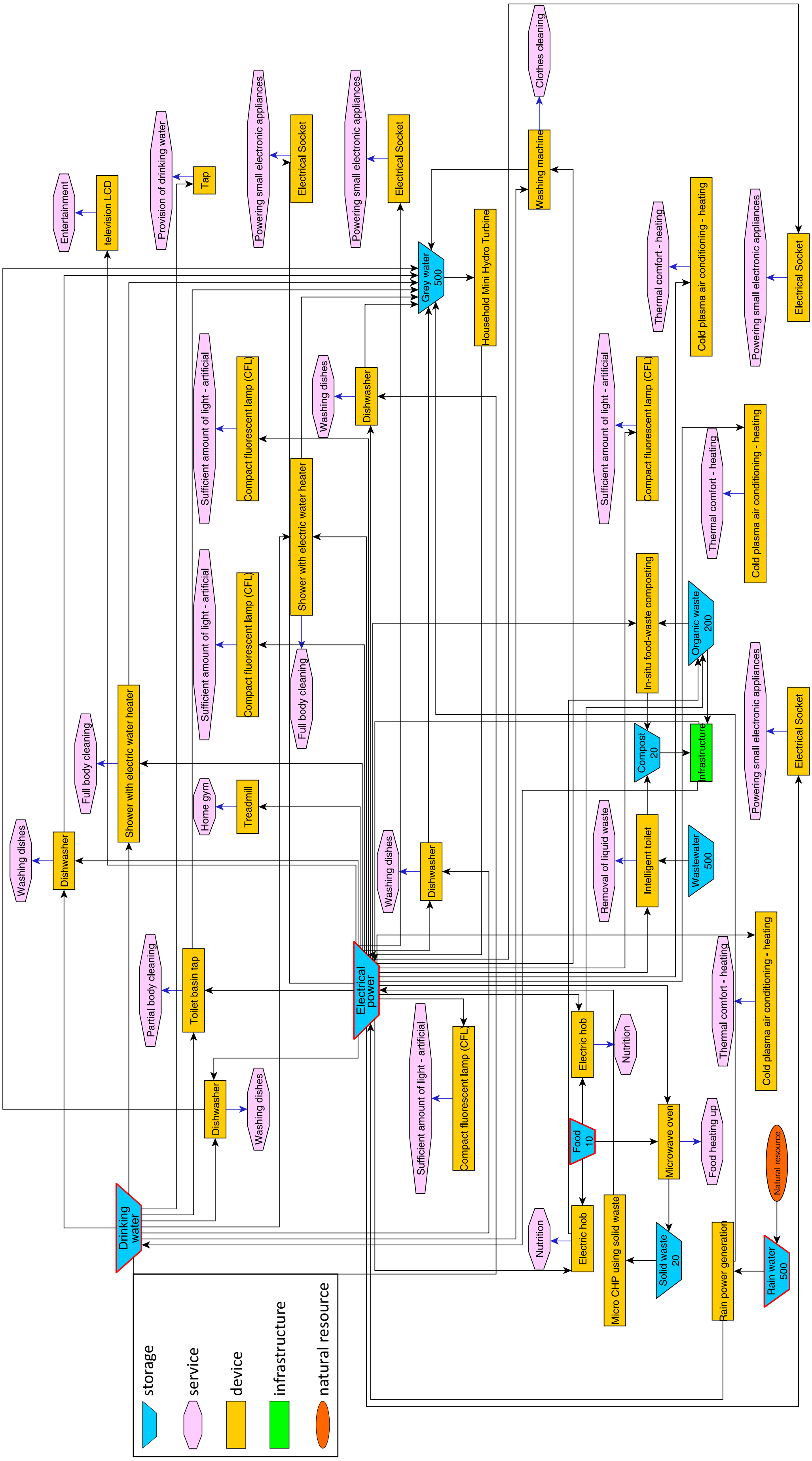


Figure 5.13: Transformation graph for Scenario D

5.2.3 "All in One" related case study

Following the ideas from the "All in One" project a household in a community is considered. This community is located in a sunny location with a close proximity to the sea. Due to the hot weather conditions there is a lack of drinking water accessible. The single utility product delivered to the household is electricity. Drinking water comes mostly from seawater, but also from recycling. However, desalination is the main process used to obtain drinking water. The process is energy intense, therefore some of the household energy demand are met through the use of sun - with the availability of the resource specified in Figure 5.14. Desalination of average seawater requires approximately 1 kilowatt-hour per cubic meter. The solution is not appropriate for a single household, but at least for a community. This solution is advisable where the fresh water is scarce. In this case study the service demand is the same as specified in Section 5.2. The problem formulation for this case study is in Appendix C.

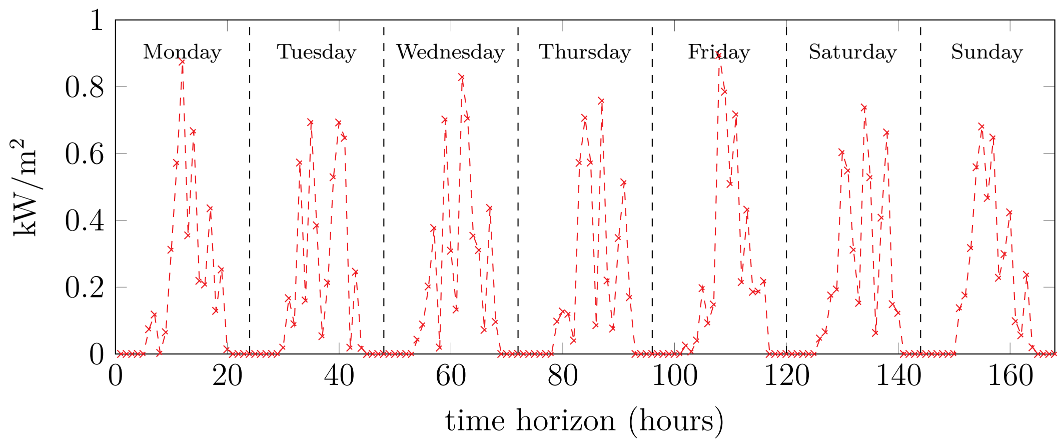


Figure 5.14: Solar irradiation

In order to built a transformation graph for this case study the shortest path approach was utilised. Using the developed shortest path interface the paths that would provide drinking water from seawater as well as waste products are investigated in order to manually build the transformation graph:

Target: Seawater -> Source: Drinking water.

The shortest paths are length 2:

- Membrane-based desalination facility + Filtration and UV water purification system;
- Membrane-based desalination facility + LifeSaver Jerrycan water filtration;

- Membrane-based desalination facility + 3.9 lpm Ultra Violet system (UV3.9WL);
- Ocean salinity power generation (reversed electro dialysis) + Modular Membrane BioReactor (MBR);
- Ocean salinity power generation (reversed electro dialysis) + Filtration and UV water purification system;

In the case of the first three possibilities, the seawater is converted into drinking water. However, in the case of the latter two, electricity is the product that connects the two devices proposed for this conversion. The output of *Ocean salinity power generation (reversed electro dialysis)* cannot be converted into drinking water. Therefore, none of the latter two would work for this purpose.

Target: Greywater -> Source: Drinking water.

The shortest paths are length 2:

- Greywater recycler + Filtration and UV water purification system;
- Greywater recycler + LifeSaver Jerrycan water filtration;
- Greywater recycler + 3.9 lpm Ultra Violet system (UV3.9WL);
- Aquaco Residential Grey Water Recycling System + Filtration and UV water purification system;
- Aquaco Residential Grey Water Recycling System + LifeSaver Jerrycan water filtration;
- Aquaco Residential Grey Water Recycling System + 3.9 lpm Ultra Violet system (UV3.9WL);
- Greywater recycler with BTM + Filtration and UV water purification system;
- Greywater recycler with BTM + LifeSaver Jerrycan water filtration;
- Greywater recycler with BTM + 3.9 lpm Ultra Violet system (UV3.9WL);
- Recover - residential water recovery + Filtration and UV water purification system;
- Recover - residential water recovery + LifeSaver Jerrycan water filtration;
- Recover - residential water recovery + 3.9 lpm Ultra Violet system (UV3.9WL);

All twelve combinations could be used for this conversion. Moreover, all devices used in the second step of these conversions are also suggested in the conversion from seawater to drinking water.

Target: Wastewater -> Source: Drinking water.

The shortest path is length 1:

- Modular Membrane BioReactor (MBR)

The most efficient from the devices in the second step in converting both from seawater and from greywater to drinking water is *Filtration and UV water purification system*. In the conversion from grewater to drinking water the most efficient one is *Aquaco Residential Grey Water Recycling System*.

The transformation graph that includes these conversions is presented in Figure 5.15. The total amount of energy that can be produced locally by *Silicon Photovoltaic system* based on data presented in Figure 5.14 is 14.4kWh in a week. Using desalination to obtain drinking water is an energy intense process. The added demand for electricity in this case study is approximately 2.4kWh per cubic metre of drinking water. The demand for drinking water in this scenario is 4000 litres in a week.

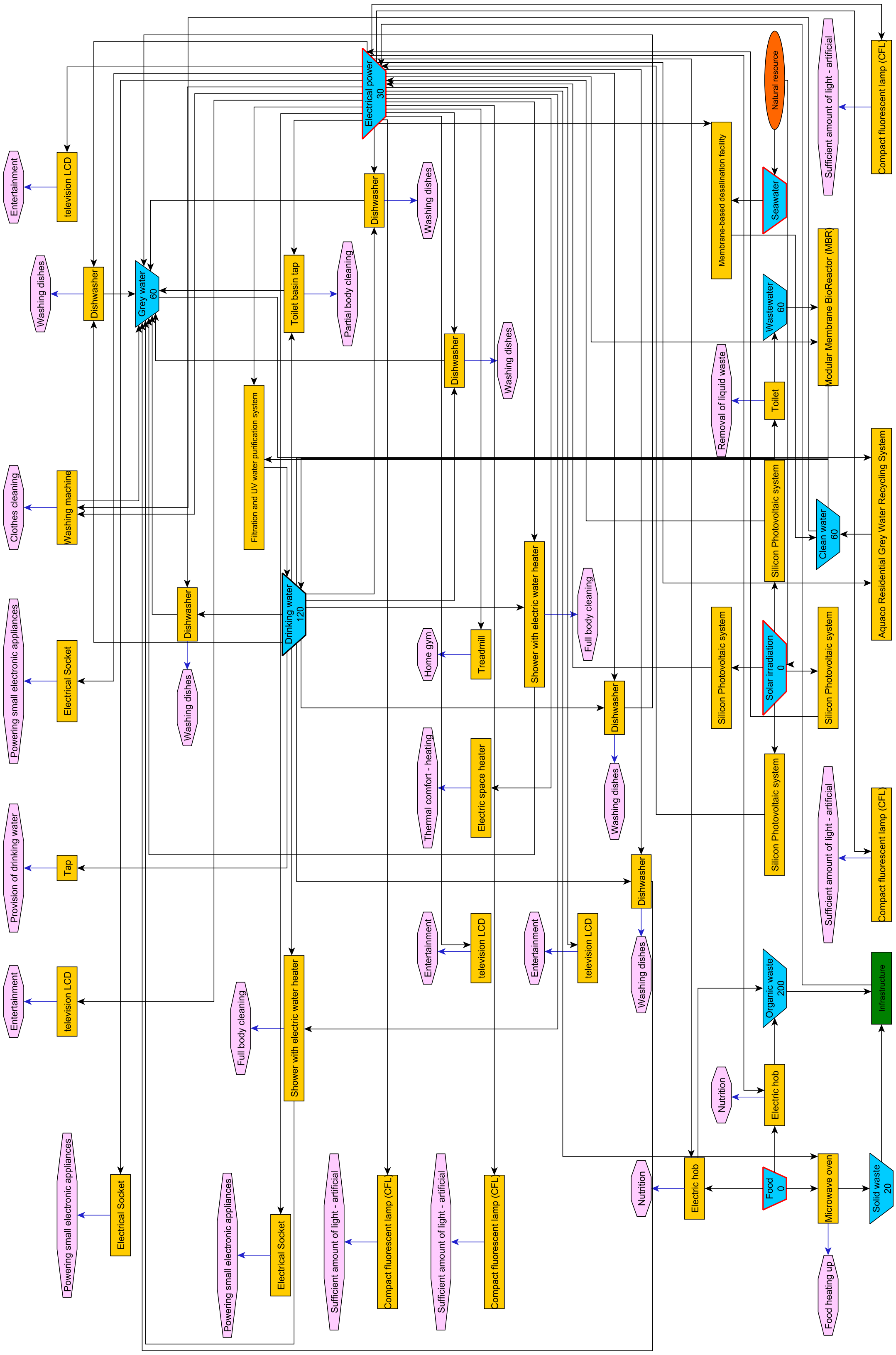


Figure 5.15: Transformation graph for “All in One” related case study

5.3 Brazilian case study

The following case study was developed for the purpose of Global Innovation Initiative – Consortium for Rapid Smart Grid Impact Project. The main focus areas was reduction of electricity consumption and demand in rural communities through education and research and investigation of possible scenarios for rural communities to become energy independent [189].

A household in the settlement Estrela Da Ilha in Ilha Solteira, located in the State of São Paulo (Brazil) visited in May 2015 and information about the products available, devices used and service demand was gathered. The location of the Ilha Solteira is presented in Figure 5.16. At the time there were 6 people living in the house located on a 14ha property. The food was mostly grown locally. The livestock kept on the farm: cows, pigs, chickens and sheep which gave the owners an opportunity to sell some of them (as well as milk and eggs). Water was supplied from a well with no quality check. There was a pipeline system to collect wastewater from the house and dispose in landfill. There is a high demand for water used for irrigation, as part of the property is used for growing corn.

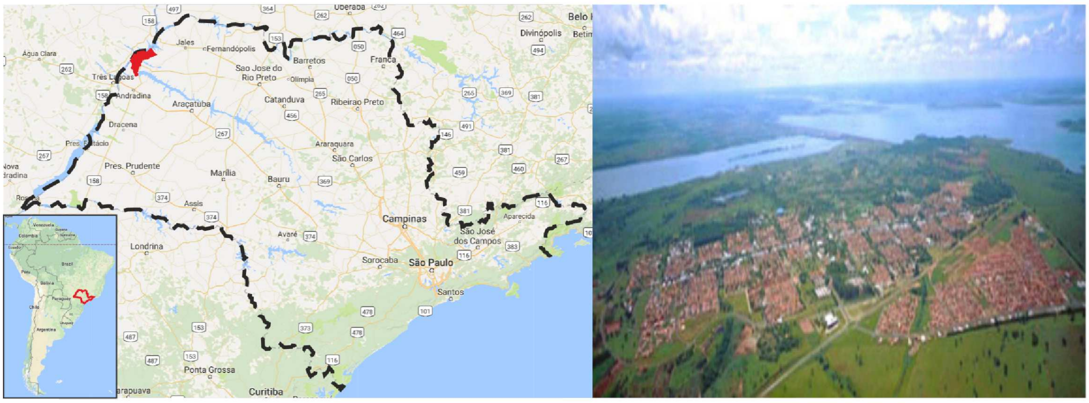


Figure 5.16: Ilha Solteira settlement

The service demand for this case study is presented in Figure 5.17 over a period of 1 week (168 hours). Moreover, there is a need for at least 1400 litres of water per day for irrigation. The main demand is in the mornings before the family goes to work and in the evenings once they return from the field. The simulation horizon is 7 days.

Devices used in the household are listed in Table 5.4. Only electricity was supplied from the grid. Natural gas was delivered to the household in bottles. The main concern of the inhabitants were the interruptions in the supply of

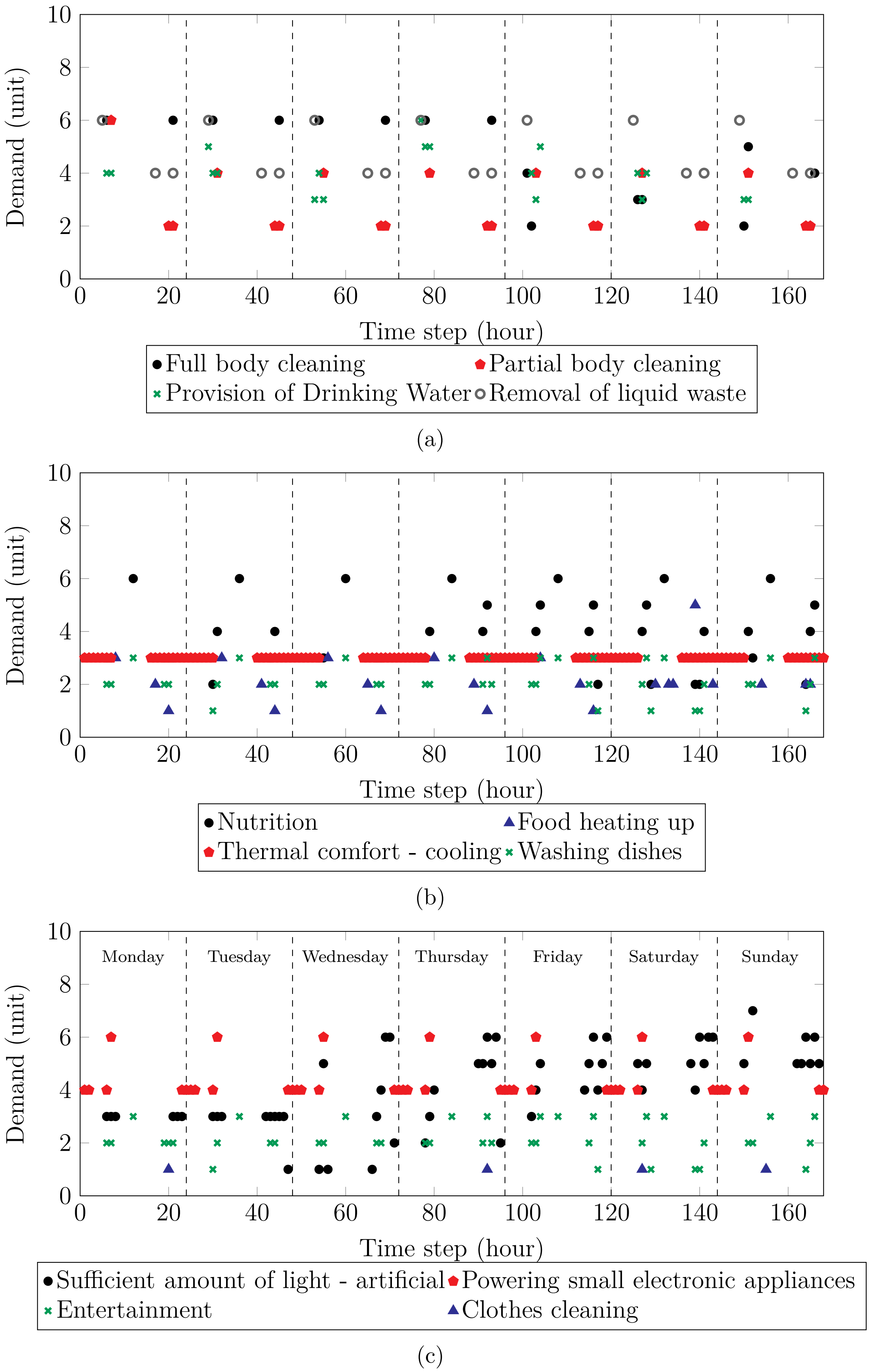


Figure 5.17: Service demand in the Brazilian case study

electricity as well as the high temperatures in the house, hence the need for air conditioning. In all rooms and corridors there are energy saving bulbs (LED). Devices used outside the house are not considered in the simulations.

Table 5.4: Devices used in the household

Kitchen – inside	Office	Bedroom x 3	Bathroom x 3	Kitchen – outside
Fridge + Freezer	Desktop computer	TV	Electric shower	Fridge + Freezer
Tap	LCD monitor	Fan	Toilet	Tap
Gas oven	Laptop		Tap	
Gas hob	TV			
Microwave	Freezer			
Toaster				

For the purpose of the GII project the temperature was monitored in one of the bedrooms for a month and compared to the data from a nearby monitoring station (Figure 5.18). It is visible that the temperature outside is on average 2 °C higher than in the house. Additionally, data was extracted from the monitoring station, such as relative humidity and global radiation (Figure 5.19) as well as average wind speed and rainfall (Figure 5.20).

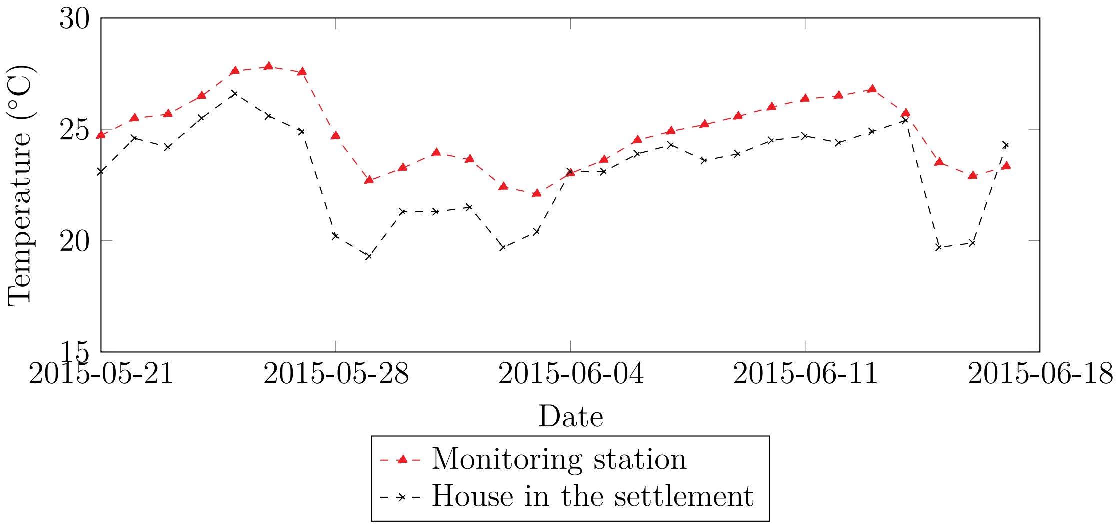


Figure 5.18: Daily air temperatures

Water could be extracted from humid ambient air, but there is no need for obtaining water in this case as there is a well. However, Figure 5.19 clearly indicates a possibility for using solar panels to obtain electricity. Unfortunately, the rainfall was very low in the investigated time period. Figure 5.20 shows one peak in the rainfall which could yield up to 40 litres of rainwater per square metre and another yielding up to 20 litres of rainwater per square metre. The majority of days were with no rainfall at all. Most wind turbines start generating electricity at wind speeds around 3-4 metres per second [190]. Therefore, this solution would not be beneficial for the considered conditions based on the information provided in Figure 5.20.

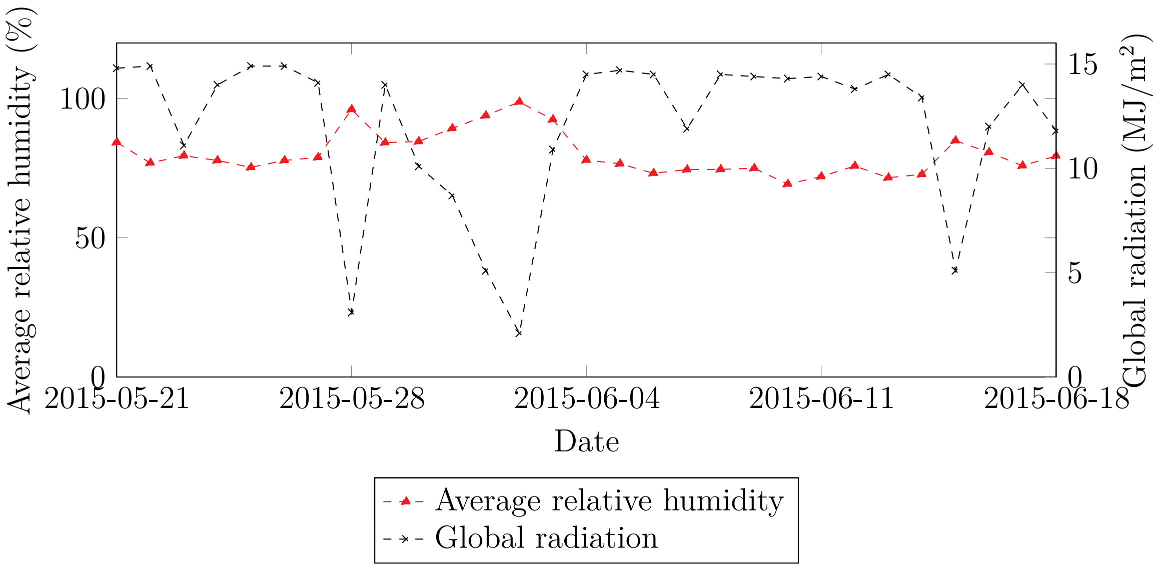


Figure 5.19: Average relative humidity and global radiation

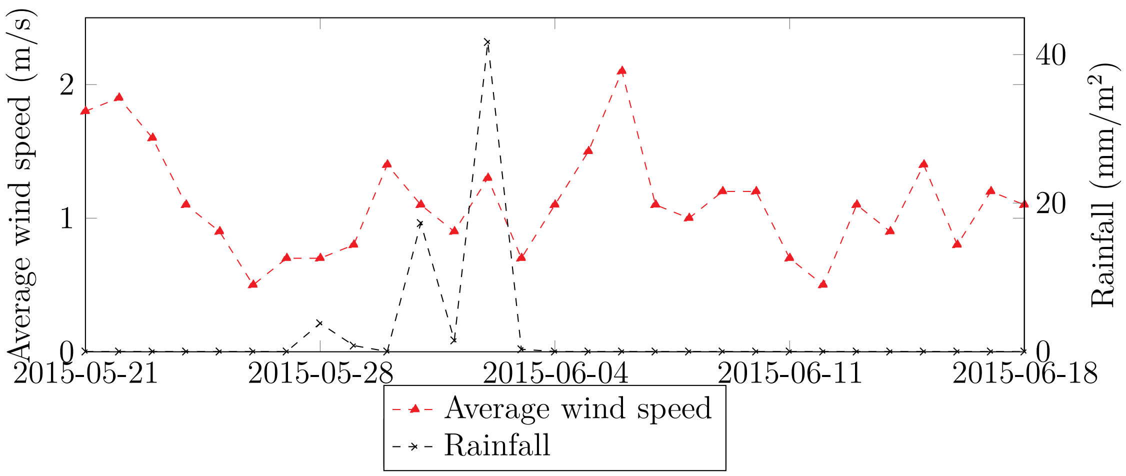


Figure 5.20: Daily average wind speed and rainfall

The main concern in this case are the interruptions in the supply of electricity from the grid. Although there is a high demand for water for personal hygiene needs and mainly for irrigation, the wastewater treatment was not considered by the inhabitants. The reason for this was the associated increased demand for energy that would come with water recycling. Additionally, the investment costs and refurbishment of the property and the wastewater infrastructure was disadvantaging this option. All water related needs are satisfied using the water from well which is at a low cost for the residents. They only need to use small amount of energy in order to pump the water.

The most appropriate solution for this case study would be a creation of a micro grid to provide electricity to the whole settlement. If solar panels with storages were used and properly maintained they could help the local residents to become independent of the main power grid.

The proposed transformation graph for this case study is presented in Figure 5.21. It includes the existing devices listed in Table 5.4 as well as replacement for the fans in a form of air conditioning units. Solar panels are proposed to alleviate some of the energy demand, but for the solution to be viable there should be a joint solar farm for the settlement. The technical specification of the solar panels stored in the XML database indicates that the maximum electricity produced, when they are not obstructed from sun, is 0.1 kWh per solar panel (PV surface is 8 square metres). This would not be sufficient to make the household independent from the grid.

Due to the large size of the property and the produce that is grown the water demand is enormous corresponding to more than 600 litres per person per day. As there are no water metres in the property the residents are not aware of their daily water consumption.

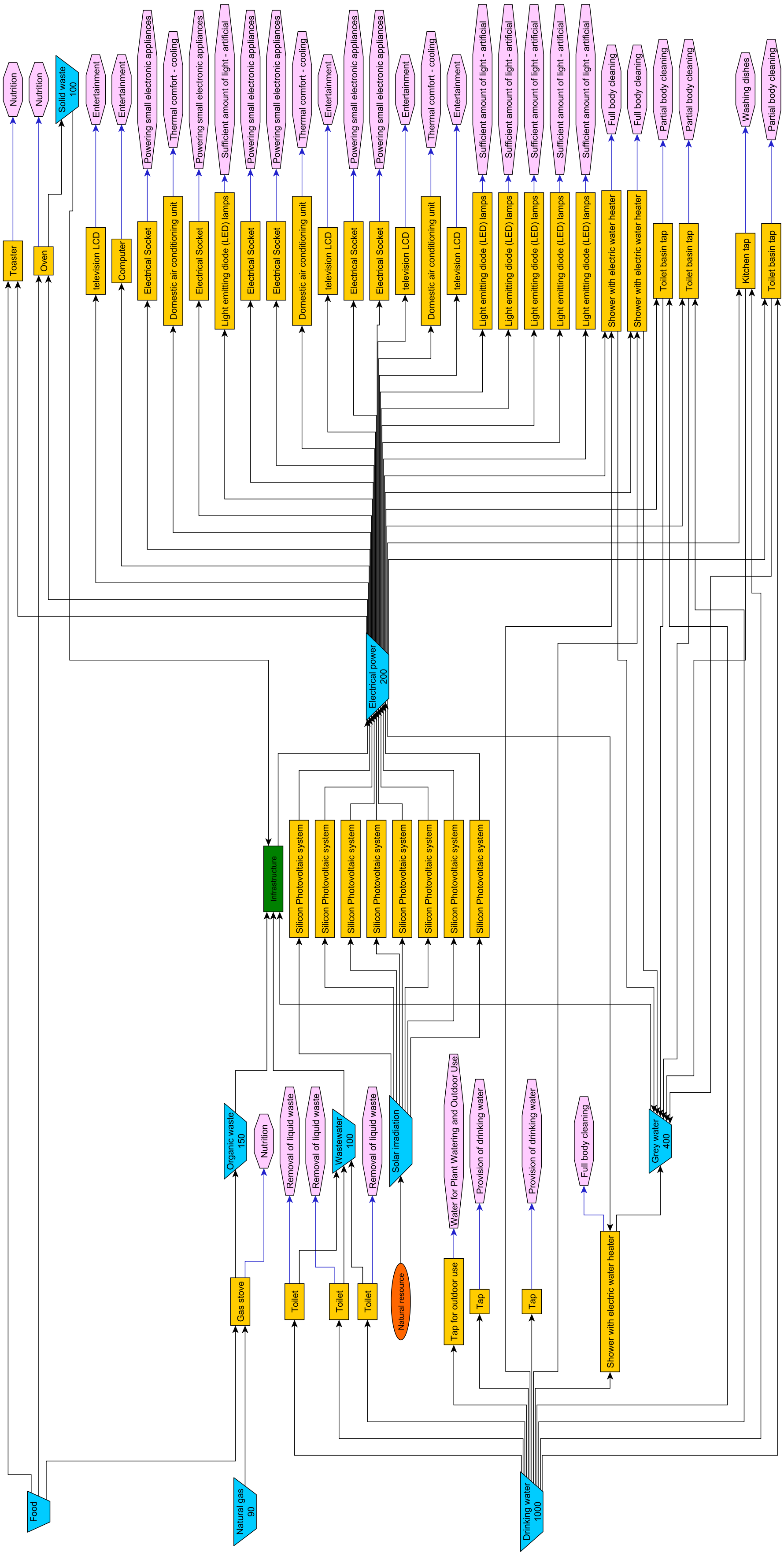


Figure 5.21: Transformation graph for the Brazilian case study

Chapter 6

Conclusions and recommendations for future work

This thesis introduced a new approach to support decision making processes while considering more sustainable solutions for resource management in households or communities. Section 6.1 summarizes the work presented in this thesis. Limitations of the proposed approach with recommendations for future research are discussed in Section 6.3. The concluding remarks are presented in Section 6.2.

6.1 Summary

The opening part of the thesis provided the glossary of key terms and definitions used in the research presented in this thesis. Chapter 1 introduced the term utility–service provision and briefly summarized the modelling approach adapted in this research. The objectives were listed in Section 1.2 followed by the contributions to the field of environmental and process engineering in Section 1.3. The list publications and presentations related to this thesis was given in Section 1.4. A short summary of each chapter was presented in Section 1.5. The first chapter concludes with Section 1.6 that summarized the research projects that utilized the developed approach.

Chapter 2 provided background for the development of the utility–service provision approach. Human needs and wants were analysed and the ones that can be satisfied by the provision of utility products were identified. In Section 2.3 water and energy consumption as well as waste management at a household level in the UK were analysed. This provided an overview of the changes in consumption patterns and helped to identify what appliances are used within households as well as what products are delivered and removed by the infrastructure. This analysis provided information that was used to populate the XML database and search for alternative solutions to the current and past approach, e.g. introduction of recycling devices to reduce the amount of drinking water that must be supplied to a household, or generation of energy from waste to minimise the amount of the former product that must be supplied by the infrastructure and minimise the amount of the latter that must be removed from a household. The first two sections of the second chapter were crucial when developing and improving the utility–service provision approach and populating the database. Section 2.4 was focused on the different definitions of sustainability and sustainable development. In this section the importance of sustainable communities was linked with Sustainable Development Goals, namely the 11th goal: “Make cities and human settlements inclusive, safe, resilient and sustainable” [92]. It is followed by revision of different approaches towards the assessment of sustainability of households and communities. The main focus was devoted to the household and urban metabolism concept and the nexus approach. The final section of chapter two summarizes the main outcomes of the “All in One” project.

In Chapter 3 the approach to model the utility–service provision was explained. The initial sections of the chapter provide an overall description of the adapted approach. In Section 3.3 the structure of the XML database was outlined, with detailed description of all its components: devices, products, technologies, services and needs as well as their connections. In the following sections the components of the utility–service provision approach were described. In Section 3.4 the problem formulation for a utility–service provision problem was explained. This section introduced its structure, the constraints that can be defined in it, such as year of the simulation, service demand, limitations of the amounts of various products that can be supplied/removed by the infrastructure, or that can be subsidised from natural resources as well as the associated costs of these processes. Additionally, the graphical user interface developed for the definition of problem formulation was presented. In Section 3.5 the concept of transformation graphs was described with its basic components: devices, services and products’ storages represented as nodes, while edges are products or service carriers. The manual approach to defining such graphs using the developed graphical user interface was explained. The simulation system developed to carry out the feasibility analysis of utility–service provision problems was explained in Section 3.6. The main components of the simulation system were described with the functionalities programmed in the interface used for simulations. The chapter concludes in Section 3.7 where the contributions to the utility–service provision model made during the “All in One” project are outlined. Moreover, changes and improvements made to the model post project are summarized.

The approach to automatically generate transformation graphs based on a given problem formulation is described in Chapter 4. The chapter contained an extended literature review on heuristic methods used for optimisation. Furthermore, it included the justification for selection of the heuristic search approach for the automatic generation of transformation graphs. The proposed approach searches the database for devices that will deliver the required services. If there are more than one available devices to deliver the service, the current transformation graph is cloned. The number of copies depend on the number of possible service devices. The algorithm progresses until all services are connected to the appropriate service device in all copies of the initial transformation graph. In the next step all products defined in the problem formulation are assigned a conversion device. If there are several devices that can process one product, an appropriate number of copies of the transformation graph are made. The algorithm ends when all products in all transformation graphs are processed. The outcome of the algorithm is a set of feasible transformation graphs.

The second part of Chapter 4 included the approach to represent the content of the XML database as a directed hypergraph - Mastergraph. In this approach products and services are nodes, and the devices are hyperedges connecting them. The use of hypergraphs was justified as devices usually connect more than two nodes, therefore the use of standard graphs was not sufficient as explained in Section 4.3. The properties of the Mastergraph were analysed to understand the connections between nodes and the robustness of the utility–service provision model. Additionally, an algorithm to find shortest hyperpaths in the Mastergraph was proposed. It allowed to search for connections between products and services or other products. The outcome of the search is the shortest hyperpath between target product and source service or product including devices required for this conversion.

The model presented in Chapter 3 was used to simulate case studies presented in Chapter 5. The heuristic search approach presented in Chapter 4 was used to find alternative solutions that introduce recycling of some products and use of naturally available resources. The case study presented in Section 5.3 was based on a real case study - a household located in Ilha Solteira in Brazil.

6.2 Concluding remarks

The aim of the research presented in this thesis was to investigate alternative approaches towards current utility–service provision solutions. Utility–service provision is focused on products delivered to households or communities via separate infrastructures and their utilization via various devices in order to satisfy basic human needs. Therefore, the following conclusions are reached:

1. The conceptualisation of the utility–service provision as an input-output system where products are delivered to households/communities, converted to other products and/or to services in order to satisfy human needs and, finally, recycled or removed from the system is very useful. It provides an insight into the complexity of the processes that occur everyday in households.
2. There are many approaches towards assessing sustainability of households or communities. Utility–service provision problems can be considered as a part of a household metabolism concept as its main focus is the direct product consumption in the household. The household metabolism refers to both the supply of resources that are indirectly required in households, e.g. energy and water needed to manufacture goods, as well as the demand for resources that are directly required in households, e.g. water for drinking and cooking. However, the utility–service provision approach provides more detailed insight into processes that occur within the household or the community.
3. Representation of the candidate solutions to a specific utility–service provision problem in a form of a directed graph provides clear visualisation of connections between each of the components in the solution.
4. The heuristic search approach offers a significant number of solutions to utility–service provision problems. They vary in terms of energy and water consumption as well as the total cost of each of the generated solutions.
5. The developed simulation system provides quantitative analysis of households' or communities' product consumption. Additionally, it provides information about the operation of each of the used devices during the simulation horizon. Therefore it provides information not only about the overall consumption, but also about the amounts of products delivered from different sources. The system can be used as a predictive tool by decision makers to asses which set of devices could be the most beneficial for their new-built or existing developments. However, it does not take into account the capital costs needed for all devices, the cost needed to modify the infrastructure if needed or the exploitation costs of these solutions. This can be potentially misleading as the supply/remove cost might be low, but otherwise it might be quite expensive. This is outside of the scope of the research presented in this thesis, but in the future should be taken into account.
6. The analysed case studies show that the developed simulation system produces results that were verified by the analysis of households' water and

energy consumption statistics.

7. The research presented in this thesis brings to attention the importance of storage technologies that could help to improve sustainability of households. Additionally, the case studies show the potential to save vast amounts of drinking water supplied by the infrastructure by introducing recycling within the household. However, this would require installing separate pipeline for greywater and clean water.

6.3 Limitation of the proposed modelling approach

The proposed approach to model utility–service provision was developed to provide a realistic reflection of processes that occur within households or communities and provide a tool that will be able to assess the amounts of products delivered/removed by the infrastructure and the associated costs. The following limitations of the approach were identified and can be considered as a base for future research:

1. Model limitation:

   – Some devices might take longer than one time step to deliver a service, e.g. some cycles for washing machines or dishwashers take more than an hour, or charging a smart phone usually takes more than one hour. In the current approach the heuristic search algorithm identifies two devices to deliver required service within a single time step. Therefore, the devices' functionality should be extended to include a possibility of delivering a service over several time steps.

   – Devices' performance changes over time. Efficiency of most devices is decreasing the longer it is used. Therefore, the life span could be included in the specification of each device.

   – Cost of maintenance of devices is not taken into account. Sometimes the cost of exploitation might supersede the daily savings that the device might be making.

   – The devices are assumed to have a fixed ratio between inputs and outputs, i.e. no dynamics. The utility–service provision could be considered as a complex system made of subsystems (devices) connected by a matrix of connections as presented in Figure 6.1. This would allow to use more accurate models of devices in the future e.g. for optimisation.

- Some storages need additional resources to operate, i.e. clean water storage might need chemicals to be added, or domestic hot water storage might need electricity source to keep the required temperature.
- Some storages could be considered as services, e.g. cold food storage.
- Similarly, removal of some products itself can be considered as services, e.g. removal of liquid waste service is equivalent to removal of graywater or wastewater. Therefore the process of removing a waste product from the system could be considered as a service.
- The number of devices used for converting natural resources should be related to the area they occupy. Therefore, the amounts available e.g. rainfall intensity or solar irradiation that are defined as unit per square metre, will be corresponding to one square metre and could be used by many devices.

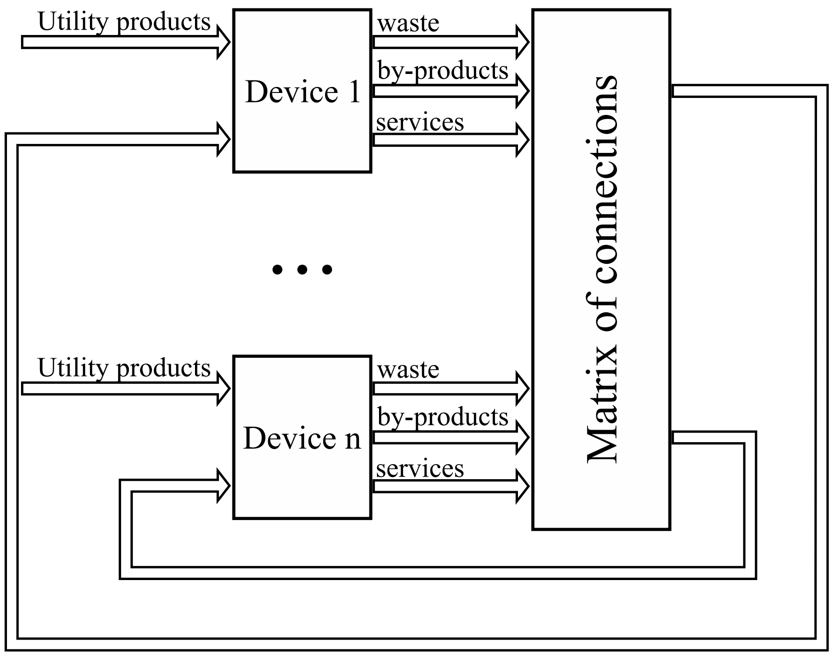


Figure 6.1: Utility–service provision as a complex system

2. Heuristic search limitation:
   - The developed heuristic search approach does not include products that are not mentioned in the problem formulation unless they are used by devices that are added to the transformation graph. Therefore, the number of possible devices that could have been included in the automatic generation might be limited.
   - The heuristic search approach builds a set of transformation graphs based on the problem formulation. The approach could be extended

to improve transformation graphs by selecting only conversion devices. This modification would enable investigating only the possibilities for recycling and use of natural resources without changes to the way services are satisfied in a household.

3. Database limitation:

   – In some cases, the inputs and outputs of only one type of device is considered from a large variety. For example, the energy consumption of a washing machine or a fridge will vary according to its size or capacity, energy efficiency rates (A+ or C).
   – Limited knowledge, expertise and understanding of the devices and technologies by the person who search and input the data. Potential human errors in the conversion of units or throughputs as well as from interpretation.
   – Limited fields. Current data only allows analyses for input-output balances. Further analyses, such as risk assessment or economic feasibility, will require more specific fields.

4. The problem formulation could be extended to a community level, i.e. by defining how many households it is composed of and what is the composition of each household. At the current state of development the problem formulation can be extrapolated to correspond to a community.
5. The optimisation is focused on the selection of the devices for the transformation graphs. However, it does not include optimising operational rules of conversion device at each time step.
6. No graphical interface to analyse the set of automatically generated transformation graphs. At the current state of development the output of the automatic generation is a CSV file that lists all the transformation graphs (used devices, total cost, total water and energy delivered via infrastructures), a set of XML files for each transformation graph and a set of GraphML files of each transformation graph for visualisation purposes. The graphical interface could help search and organise the results.
7. Limitation for real design situation:

   – The case studies presented in Chapter 5 show how the developed simulation system and the automatic generation work. The approach developed in this thesis could be useful for designing or re-designing a house or a community to make it more water/energy/cost efficient. However, in order for the system to provide reliable results the database would have to be constantly updated. This could provide a benefit for companies as they could adapt the database to feature their products.

  - This system generates a very high number of possible solutions which are not easy to analyse and select “the best one”. This would be confusing to any type of user not familiar with the system. In order to make this system work in real life application the number of the solutions would have to be limited significantly.
  - Some changes in the graphical user interface would also be beneficial in order to make this approach work beyond academic research stage. At this stage of development the designed interface is not intuitive as it was not designed to be used outside the “All in One” project and PhD research.
  - Some features would have to be added to the approach to make it useful for house owners and developers. These include taking into account space that various devices occupy, or the installation and delivery costs.

6.4 Recommendations for further research

In the previous section the limitation of the proposed approach were summarised. The future work on the simulation system includes:

- Development of the graphical user interface for manipulation of the automatically generated transformation graphs. It would be beneficial to have different criteria for comparison of the solutions to help with selection of the most appropriate one for the given set of constraints.
- Improvement of the graphical user interface for manipulation of data in the XML database. The device tab should be extended to enable division into conversion devices and service devices.
- Introduction of additional fields describing devices, i.e. size, initial cost, maintenance cost, lifespan, or time required to deliver a service.
- Extension of the optimisation of the solutions. In the first instance the developed algorithm should be revised to limit the number of possible transformation graphs. In the second instance the predictive control models could be used to adjust operational rules of the devices. The utility–service provision problem can be formally described as a linear programming problem and existing solutions such as IBM ILOG CPLEX can be used to optimise the operational rules of devices.
- Extension of the automatic generation to conversion devices only. It would be beneficial to have a alternative options for the set of conversion devices only.

– Extension of the modelling approach to a community level. A standardized set of service demands and service devices could be applied to a number of households. These households could be treated as individual components of a larger system, and the conversion devices could be added on a community level. As Daniel M. Kammen wrote "... applying green construction to multiple buildings at once may be an even better idea. Sharing resources and infrastructure could reduce waste, and retrofitting impoverished or moderate-income neighbourhoods could also bring cost savings and modern technology to people who would typically lack such opportunities. Working at the neighbourhood level does add complexity to planning, but these neighbourhood efforts offer rewards that even green single-family homes cannot offer" [191, p.30].

General recommendation for the research and future development of households and communities are:

– Planning for the recycling of resources in household/communities should be planned at an early stage of development. Separate water networks should be planned for to enable reducing the amount of drinking water supplied from the infrastructure.
– Emphasise to the citizens the importance of saving resources. There is a vast amount of technologies available for conversion of natural resources into energy and drinking water or for recycling and treating products on a small scale. However, if the public is not aware of them and their importance, they will not invest in them.
– Influence the developers to include resource saving/recycling options in their developments. If such solutions are required by law, they will become commonplace.

Appendix A

A.1 XML database content editor

The software enables adding/removing/editing of products, devices, services, needs and technologies, as well as problem formulations and transformation graphs with eight separate tabs. The eighth tab is devoted to shortest hyperpaths calculations.

First the files for each tab must be loaded by pressing "Load Files" button as presented in Figure A.1. Other functions are inactive until the files are loaded.

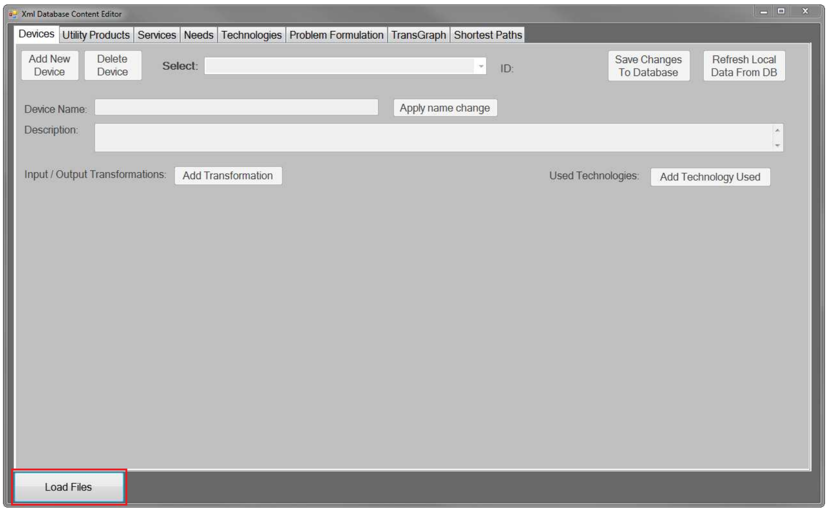


Figure A.1: XML database content editor – load files screen

The functionalities of tabs 1-5 are similar with the tab for devices being the most complex one, see Figure A.2. Therefore they are explained using the device tab:

1. Save changes to database – All changes made (adding/editing/removing devices/products/services etc.) are done on local data, i.e. are not reflected in the DB until the button "Save changes to database" is clicked . This button uploads all local data (devices, utility products, services,

needs, technologies, problem formulations and transformation graphs) to the database. This button appears on all seven tabs.

2. Refresh local data from DB – overwrites the local data displayed in the software with the data currently stored in DB. This button is used when the changes made on local data need to be discarded. This button appears on all seven tabs.
3. Add New Device – creates new device with an unique id displayed in 6.
4. Delete Device – deletes selected device.
5. Select – list of devices in the database. Selected device can be edited.
6. Device ID – states the device's ID that is unique.
7. Device Name – displays device name. When a new device is added the name has to be assigned.
8. Apply Name Change – changes the name of the device in the database.
9. Description – allows to include description and references for the device.
10. Add Transformation – enables to define operational rules for the device.
11. Buttons corresponding to the operational rules of the device (transformation). Their functions are (from left to right): add device input, add product output, add service output and remove this transformation.
12. Technologies used by a device. A device can use multiple technologies. Each technology has an assigned year of availability, which specifies if the device can be used for a particular candidate solution.
13. Fields corresponding to the amount of products required (on input) with units.
14. Fields corresponding to the amount of products and services produced (on output) with units. There are no units for services.
15. Remove buttons for each of inputs/outputs. Individual inputs and outputs can be removed by clicking on corresponding "Remove" button.
16. Max throughput defines up to how many units of product/service a device can produce per 1 hour.

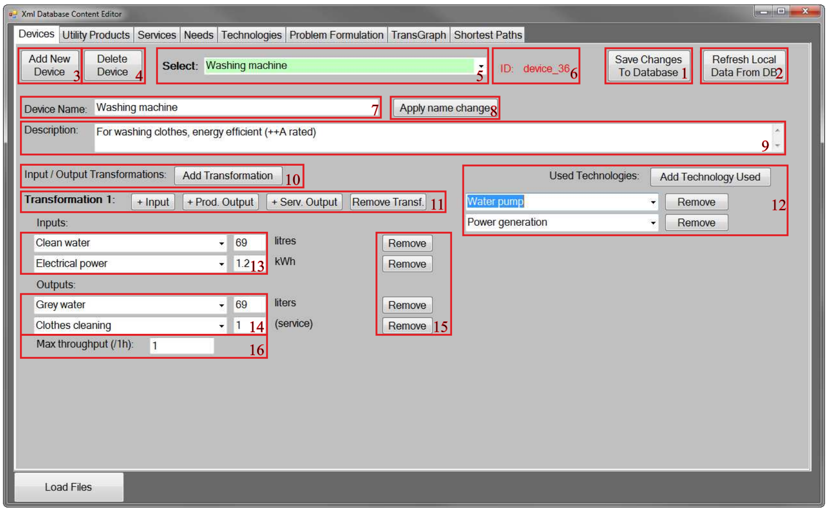


Figure A.2: XML database content editor – device tab

A.2 Problem Formulation Tab

This tab is designed to simply definition of problems that can be simulated (Figure A.3). Functionalities 1 to 8 are analogous to tabs 1-5. The remaining ones are:

9. Simulation year – the year for which the utility–service provision problem is considered.
10. Save Problem Formulation to XML file – exports current problem formulation to an XML file that can be used in the simulation system.
11. Time horizon – specification of the simulation horizon. Can be in hours, days or years. It is later converted to hours to be used in the simulation system.
12. Add new service – Services can be selected from a list and confirmed by pressing a button "Add new service".
13. Service demand specification – A table with the demand corresponding to each time step is created for each service with "Remove service" button in case the service must be removed.
14. Add new product – similarly to service selection, products can be selected from a list and confirmed by pressing "Add new product" button. However, if a product is already added to a prohibited product list, it will not be possible to add it here. It must be first removed from the prohibited list.
15. Products specification – For each product firstly must be specified whether it can be supplied and removed by the infrastructure. Checking the appropriate checkboxes will add columns in the table located below. If a product can be supplied by the infrastructure (the "Can supply" checkbox is checked) columns "Max supply" and "Supply cost" will be visible. "Max

supply" column corresponds to the maximum amount of this product that can be supplied by the infrastructure in a single time step. "Supply cost" corresponds to the cost of a single unit. There is a possibility to have different costs depending on the time step. It is useful when e.g. there are different day and night tariffs for energy supply. It is analogous for "Can remove" checkbox, and "Max remove" and "Remove cost" columns. There is also a possibility to define maximum capacity of an associated storage that will be used in the transformation graph.

16. Add new prohibited product – Create a list of products that cannot be used in the transformation graph by clicking "Add new product" button. If a product is already defined in the list of products, it will not be possible to add it to the prohibited products list.
17. List of prohibited products with "Remove product" buttons that enable product to be removed from this list and used in the transformation graph.

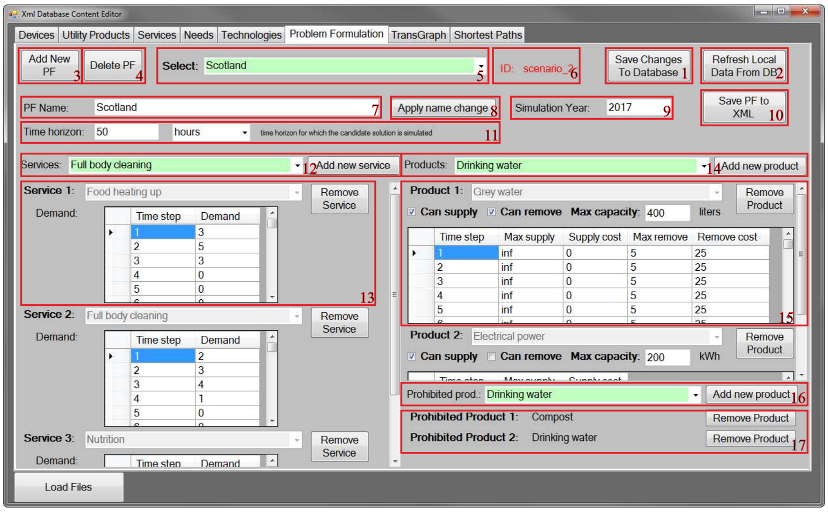


Figure A.3: Problem Formulation Tab

A.3 Transformation Graph Tab

This tab is designed to simplify manual definition of transformation graph (Figure A.4). Functionalities 1 to 6 are analogous to tabs 1-6. The remaining ones are:

7. Associated Problem Formulation – in order to start defining a transformation graph a specific problem formulation must be selected. It can be selected from a list of previously defined problems stored in the database.

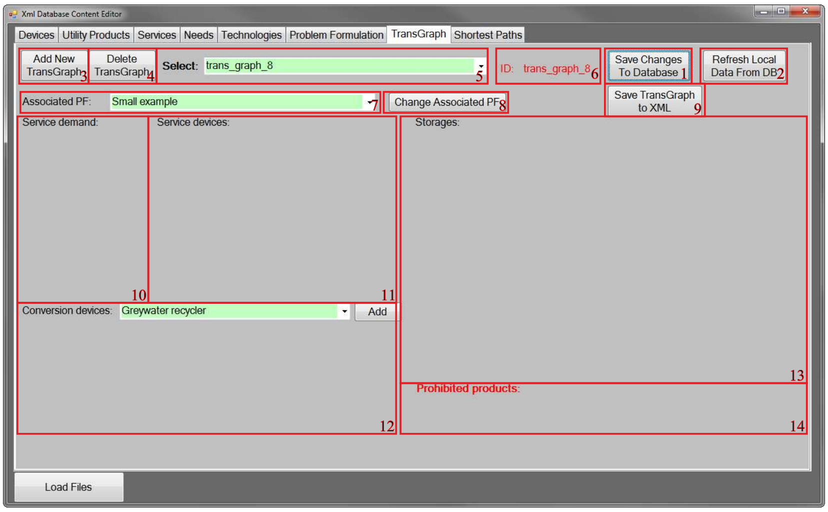


Figure A.4: Transformation Graph Tab

8. Change Associated Problem Formulation – confirm the problem formulation that the current transformation graph is supposed to address. If the transformation graph is new and does not have an associated problem, this must be selected prior to the definition of service devices, conversion devices and storages. Based on the associated problem formulation a list of service demand nodes (10), space for service devices definition (11), space for conversion device definition (12), storages (13) and prohibited products list (14) will be generated.
9. Save TransGraph to XML file – exports current transformation graph to an XML file that can be used in the simulation system.

Once the associated problem formulation is assigned a list of service demand nodes is generated (marked in Figure A.5 as 1). Next to each service node a list of available service devices is generated (marked as 2). The available service device list excludes devices that use prohibited products defined in the associated problem formulation. The devices can be selected from a drop-down list and their selection confirmed when prompted (marked as 3). When a device is selected a new column appears on the left next to the defined service demand. There will be as many columns as selected devices. Additionally, each device's inputs and outputs are checked against existing storage list. If a storage does not exist, appropriate node is added. The missing storages will appear in the storage list on the right. Each device is also added to the storage's inputs and outputs.

Conversion devices can be selected from a drop-down list marked as 1 in Figure A.6. The list of available devices is based on the prohibited products list from the associated problem formulation. Once the device is selected it must be added by clicking "Add" button indicated as 2. The list of selected conversion devices appears underneath (marked as 3). Inputs and outputs for each device

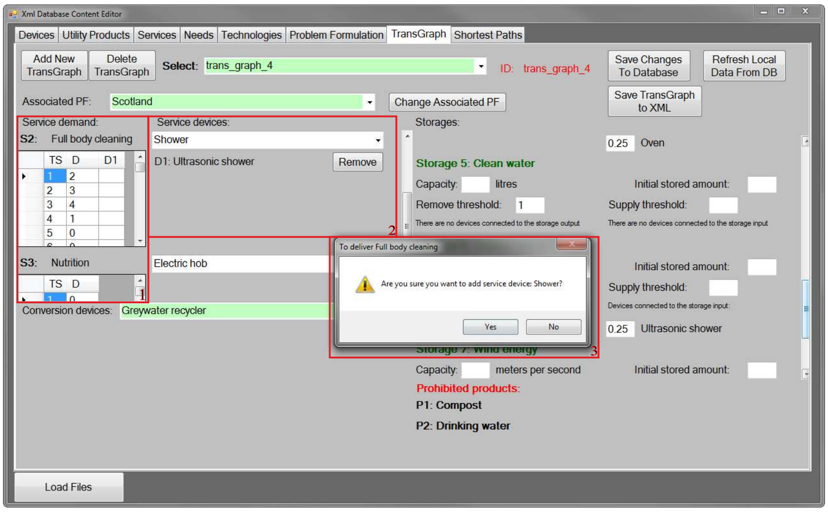


Figure A.5: Transformation Graph Tab - service devices selection

are shown for information about products that might need to be reused. All inputs and outputs are checked against existing list of storages. If any of them are missing, appropriate storages will appear in the storage list.

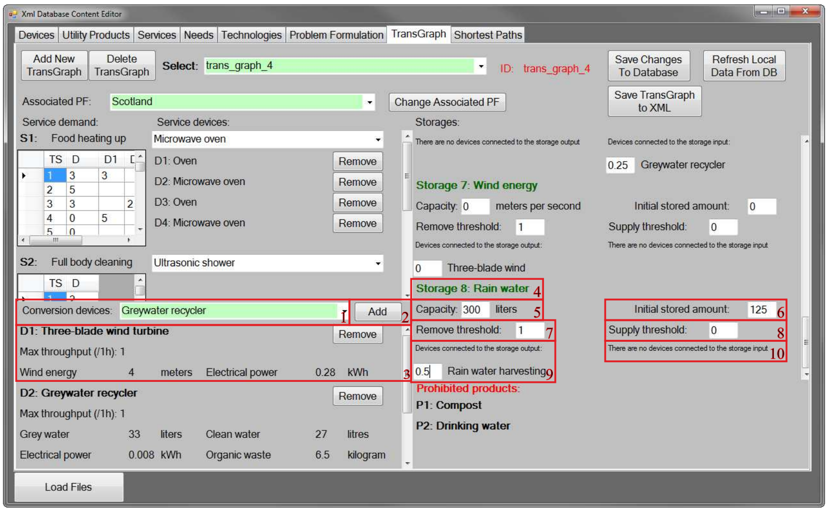


Figure A.6: Transformation Graph Tab - conversion devices selection & storages

Storages to all products defined in the problem formulation as well as all products used by the devices added to the transformation graph are automatically added to the storages list (indicated as 13 in Figure A.4). Each storage specifies the name of the product it is storing (indicated as 4 in Figure A.6). For each product storage the following must be defined:

5. Capacity. Sometimes the storage is just theoretical, e.g. solar irradiation cannot be stored, therefore its capacity must be 0.
6. Initial stored amount – optional field. If not defined it will be assumed to be 0. It is the amount of product that is stored at the beginning of the simulations.

7. List of devices connected to storage output – corresponds to the “push to device threshold”. It specifies when the product will be pushed to a device. The default value is “0.75”. There can be many devices connected to the same storage output. These values give them “priority” for processing specific product. When there are no devices connected to the storage output, a message “There are no devices connected to the storage output” will appear.
8. List of devices connected to storage input – corresponds to the “pull from device threshold”. It specifies when product will be pulled from a device. The default value is “0.25”. There can be many devices connected to the same storage input. when there are no devices connected to the storage input a message “There are no devices connected to the storage input” will appear.

Appendix B

B.1 Basic concepts on set theory

Some basic concepts from set theory that have been used throughout the thesis are summarized here.

A set is a grouping of objects. Sets are usually represented with upper-case Latin letters: $E, H, N, T, \ldots$ The objects belonging to the set are called elements and are usually represented with lower-case Latin letters: $n, e, x, \ldots$ [192].

The symbols used [193]:

equality symbol	$=$
membership symbol	$\in$
empty set	$\emptyset$
logical connectivities	$\wedge$ (and), $\vee$ (or)
quantifiers	$\forall$ (for all), $\exists$ (exists)
subset	$\subset$
Union $T \cup E$	for $\{x : x \in T \vee x \in E\}$
Intersection $T \cap E$	for $\{x : x \in T \wedge x \in E\}$
Difference $T \setminus E$	for $\{x : x \in T \wedge x \notin E\}$

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